STUDY ON NON-EXHAUST EMISSIONS IN ROAD TRANSPORT

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Air pollution remains a major global challenge, with particulate matter (PM) pollution continuing to pose serious health and environmental risks. Many urban areas exceed World Health Organization (WHO) air quality guidelines, leading to adverse health effects, such as respiratory and cardiovascular diseases, and increased healthcare costs. As tailpipe emissions decline, Non-Exhaust Emissions (NEEs) from road transport—including particles from brake, tyre, and road wear—are becoming a dominant contributor to urban PM pollution. NEEs not only affect air quality but also contaminate water and soil, raising concerns about microplastic pollution and ecosystem health. However, significant data gaps remain regarding NEE emission factors, chemical composition, and specific health effects, making regulation and mitigation more challenging. This report examines the sources, impacts, and mitigation strategies for NEEs, using London as a case study to evaluate different policy and technical interventions. Modelling results for London are available via a publicly accessible Microsoft Power BI. The study has been conducted by e:misia in collaboration with EIT Urban Mobility, Transport for London (TfL), and the Greater London Authority (GLA).

Main sources of non-exhaust emissions

Brake wear emissions are currently the largest source of NEEs in urban areas, as frequent acceleration and deceleration release significant amounts of particles—over 40% of which become airborne. However, regenerative braking in electric vehicles (EVs) significantly reduces brake wear, lowering emissions by over 80%. Additionally, EVs completely eliminate exhaust emissions, improving overall air quality.

Tyre wear is the second-largest source of NEEs, but only 1–5% becomes airborne, with the remainder accumulating in road dust, water systems, and soil. Emissions are higher in urban areas due to frequent acceleration, braking, and cornering and tend to increase in warmer temperatures, indicating potential exacerbation due to climate change. Additionally, heavier vehicles, including EVs (which are on average 20% heavier than internal combustion engine (ICE) vehicles), generate more tyre wear, raising concerns about long-term particulate pollution trends.

Road wear emissions are harder to quantify, as they mix with tyre wear particles and resuspended road dust. While their airborne contribution is relatively small compared to brake wear, they remain a concern, particularly in cities with poor road maintenance. Well-maintained road infrastructure can play a key role in mitigating these emissions.

Overall, increased emissions from tyre and road wear from electric vehicles are offset by reduced brake wear emissions and removal of exhaust emissions. As such, fleet electrification is overall positive from an air quality perspective.

The upcoming Euro 7 regulation, set to take effect from late 2026, will introduce new limits on PM emissions from brake wear, with tyre wear limits following two years later. These measures aim to mitigate NEEs, but their full impact will take time to materialize, as the regulation only applies to new vehicles, leaving the existing fleet unaffected. Additionally, there are potential trade-offs to consider, including the risk of using potentially more toxic materials in low-wear brake and tyre designs. Encouraging the early adoption of wear-resistant components across all fleets could accelerate Euro 7 benefits, but careful material selection is essential to avoid unintended health and environmental consequences.

Key recommendations

Based on these findings, the report recommends a multi-level policy approach to effectively reduce NEEs. At the local level, cities should take full account of NEEs within air quality policies, consider expanding Low Emission Zones (LEZs) and promoting sustainable transport initiatives such as improved public transport and active travel infrastructure. A modal shift from private vehicles to public transport emerges as the most effective strategy for reducing NEEs, with the potential to achieve up to five times the impact of fleet electrification alone.

While fleet electrification remains beneficial, particularly due to fleet decarbonization, eliminating exhaust emissions and reducing brake wear, its overall impact on NEEs is less significant than reducing vehicle kilometres travelled via mode shift. Additionally, promoting smoother driving behaviours—such as reducing speeds, optimizing driving styles, and enhancing traffic flow—can further minimize brake, tyre, and road wear emissions.

At the national level, governments should support the implementation of Euro 7, encourage the early adoption of low-wear vehicle components, and increase public awareness of both low-emission transport options and wear-resistant vehicle technologies beyond continuing to support fleet electrification. At the international level, greater collaboration is needed to standardize monitoring protocols, address potential toxicity trade-offs, and secure funding for further research targeting the knowledge gaps around NEEs and their mitigation strategies.

Addressing non-exhaust emissions is crucial for sustainable air quality improvements and public health protection. While Euro 7 and fleet electrification will help reduce NEEs over time, mode shift remains the most effective strategy. A comprehensive approach, combining technology, regulation, urban planning, and behavioural change, is essential for reducing NEEs, improving air quality, and ensuring long-term environmental sustainability.

1 The importance of reducing particulate matter in cities

Air pollution is a major global health crisis, responsible for millions of premature deaths annually [1]. Particulate matter (PM)—especially the fine particles generated by road transport—pose a serious threat to public health and the environment. In urban areas, non-exhaust sources such as brake, tyre, and road wear now dominate PM emissions [2] making them an important area to focus efforts on to reduce pollution.

PM comprises a complex mix of solid and liquid particles suspended in the air, including PM_{10} (particles with a diameter of 10 microns or less), $PM_{2.5}$ (particles with a diameter of 2.5 microns or less) and ultrafine particles $PM_{0.1}$ (particles with a diameter of 0.1 microns or less). Exposure to elevated PM levels has been linked to both short- and long-term health conditions, including respiratory symptoms such as coughing, shortness of breath, wheezing, asthma, and respiratory diseases, as well as severe cardiovascular conditions, neurological disorders, cancer, and, ultimately, premature death. Particles smaller than 2.5 microns are especially dangerous due to their ability to penetrate deeply into the lungs and the blood stream [3].

Whilst there are health impacts as outlined, there are also economic impacts of air pollution which have been quantified in the EU Handbook of External Costs of Transport [4] and in a recent UK-focused study [5] for air quality damage costs, underscoring the economic burden of PM emissions on urban centres. This captures costs associated with hospitalisations, symptom days, work absences, mortality, and environmental benefits like improvements in soil and water quality, ecosystem services, and climate change mitigation. The damage cost values are provided per pollutant, sector, country, and, in some cases, adjusted based on population density. Specifically, for PM_{10} in road transport, an average value per country is used, while for $PM_{2.5}$, costs are differentiated by metropolitan areas, cities, and rural areas. For example, in central London, the damage cost from road transport is estimated at 473 EUR per kilogram of $PM_{2.5}$ emitted (based on 2022 values) [5]. This means that the 25.4 kilotons of $PM_{2.5}$ emitted from road transport (including both exhaust and non-exhaust sources) in central London in 2019 resulted in a total cost exceeding 12 million EUR for that year alone.

Key finding #1.1: Exposure to particulate matter (PM) air pollution has serious health and economic consequences, contributing to chronic illnesses and premature mortality. Fine particles (PM2.5) are particularly hazardous due to their capacity to enter deep lung tissue and the circulatory system.

In 2021, the World Health Organization (WHO) updated its air quality guidelines for the first time since 2005 [6] based on the latest health evidence. The annual limit was lowered for PM_{10} from 20 µg/m³ to 15 µg/m³ and for $PM_{2.5}$ from 10 µg/m³ to 5 µg/m³. More than 96% of the European population was exposed to $PM_{2.5}$ concentrations exceeding the WHO annual limit in 2022. For PM_{10}, this was 83%. To align with these stricter guidelines, the European Council and Parliament agreed to strengthen current EU air quality standards [7].

In urban areas, where high population density and vehicular traffic contribute significantly to air pollution, addressing particulate matter (PM) emissions is crucial. In London, air quality improvements have been ongoing, with substantial reductions in $PM_{2.5}$ levels since 2016, as shown in Figure 1. Data from the London Atmospheric Emissions Inventory (LAEI) [8], updated every three years, indicates that annual average $PM_{2.5}$ concentrations across London were reduced to 10.8 µg/m³ in 2019, 19% lower than in 2016.

The average $PM_{2.5}$ concentration is expected to further decrease to around 9.7 µg/m³ by 2025 and 8.8 µg/m³ by 2030. The number of monitoring locations exceeding the interim WHO target of 10 µg/m³ has significantly reduced over the years, however seven sites were still exceeding in 2023 [9].

This improvement in emissions is largely attributed to the implementation and expansion of key policies focused on reducing air pollution and protecting public health. However, even with these advances, it has been estimated that around 4,000 premature deaths occurred in London in 2019 as a result of air pollution [1]. The LAEI forecasts indicate that without additional interventions, the latest WHO guidelines for $PM_{2.5}$ are unlikely to be met across London by 2025 or 2030. In response, the Mayor of London has committed to achieving the latest WHO interim target for $PM_{2.5}$ of 10 µg/m³ London-wide by 2030 and achieving the ultimate guideline value of 5 µg/m³ as soon as possible. This advances the target a decade ahead of the UK legal limit established in the Environment Act 2021 [10]. However, data indicates that achieving this target and the ultimate guideline value across Greater London will require sustained and bold measures to be implemented without delay.

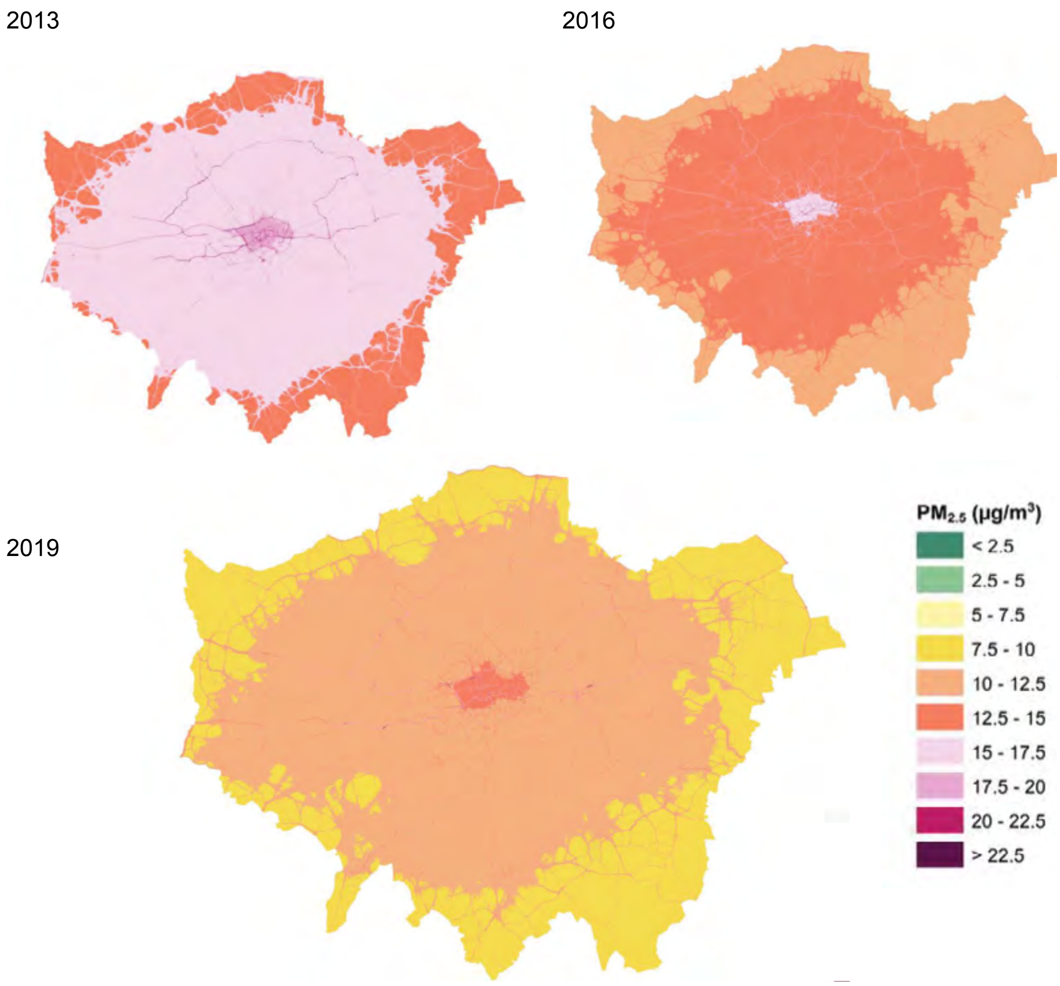


Figure 1: Image of $PM_{2.5}$ concentrations in Greater London over time. Data from LAEI (2019).

Despite progress in reducing PM2.5 levels, meeting updated WHO air quality guidelines remains difficult in cities, including London. Additional measures are essential to achieve these stricter standards across all areas by 2030. Non-exhaust emissions from road transport, including brake, tyre, and road wear, are the primary contributors to particulate matter pollution in urban areas. Road dust resuspension also adds to PM levels, though its sources can be varied and not exclusively transport related.

Key finding #1.2: Addressing the primary non-exhaust sources is essential for meeting WHO air quality targets and mitigating the health impacts of urban air pollution.

Given the growing contribution of NEEs to urban air pollution, understanding their specific sources and quantifying their impact is essential for developing effective mitigation strategies. The following chapter provides a detailed breakdown of non-exhaust emissions, examining their role in particulate matter pollution and assessing how different urban policies and vehicle technologies influence their levels.

2 Breakdown of non-exhaust emissions by source

Non-exhaust emissions from road transport—brake, tyre, and road wear—are increasingly recognised as a significant source of urban air pollution, yet precise attribution of these sources remains challenging. This chapter examines the contribution of non-exhaust emissions to particulate matter (PM) pollution in London and compares these findings with available data from other European cities, highlighting the impact of vehicle electrification and urban policies.

2.1 The case of London

The London Atmospheric Emissions Inventory (LAEI) includes data for the contribution of each sector to PM. Road transport contributed c.27% of total PM_{10} and more than 30% of total $PM_{2.5}$ emissions in 2019 in Greater London. Figure 2 shows the evolution of PM_{10} and $PM_{2.5}$ by source in Greater London both for historical years (2013, 2016, 2019), and projections based on the LAEI data from 2019 [8]. Due to factors such as advancements in engine and exhaust after treatment technology (e.g. diesel particulate filters) and the gradual rise of electric vehicles, PM_{10} emissions from road transport reduced by 9% in 2019 compared to 2016 and are expected to further reduce by 16% in 2025 and another 16% in 2030 without any further actions.

A similar reduction stands also for $PM_{2.5}$ and equals to 14% from 2016 to 2019 with an additional 21% expected by 2025 and another 15% between 2025 and 2030. Alongside exhaust emissions, actions are also needed to target non-exhaust emission sources which have become the dominant contributor of PM_{10} and $PM_{2.5}$ in road transport not only in London but also at a national level as indicated in official national UK data [11], [12]. At a UK level, non-exhaust emissions account for 90% of road transport PM_{10} and 80% of road transport $PM_{2.5}$, with further increases forecast to 2030.'. Similar values for the European Union have been indicated in another study [13].

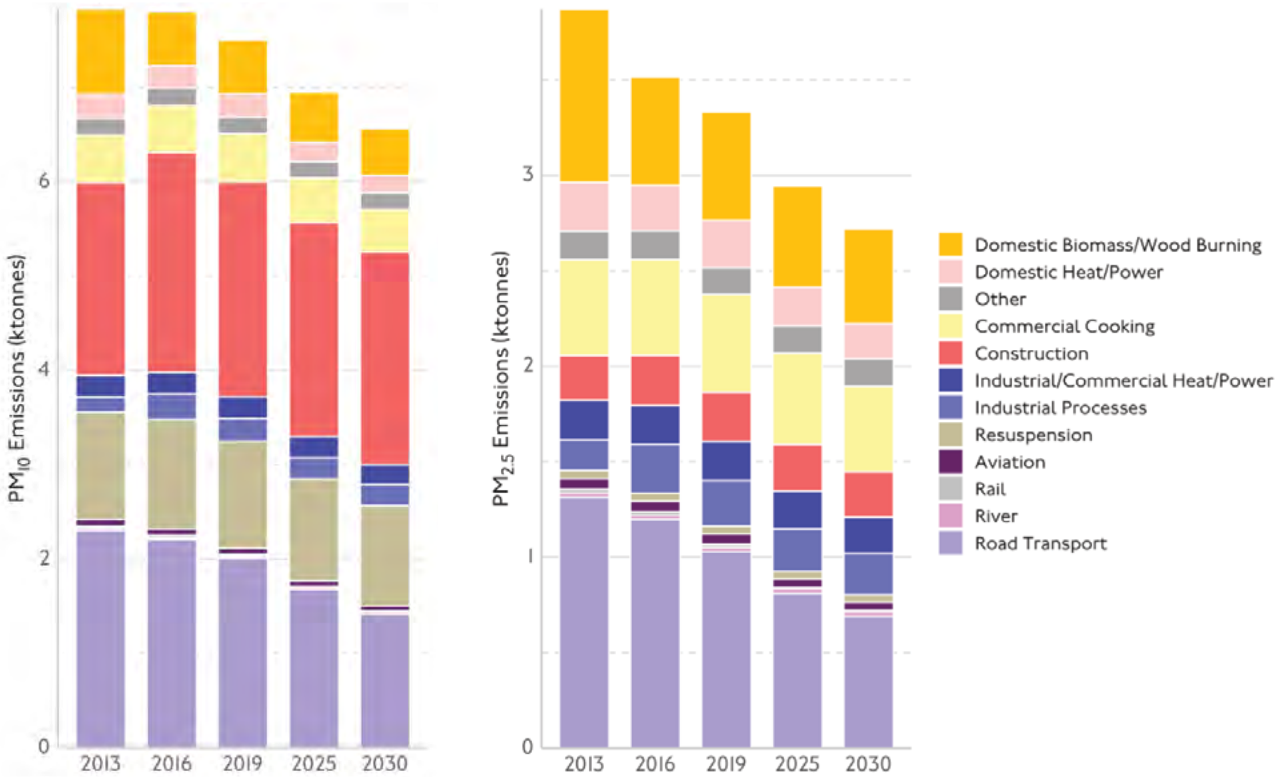


Figure 2: Image of the evolution of PM emissions by source in Greater London: (left) PM$_{10}$ (right) PM$_{2.5}$. Data from LAEI (2019).

The PM$_{10}$ and PM$_{2.5}$ emissions from road transport in London are shown in Figure 3 and Figure 4, including exhaust emissions and emissions from brake and tyre wear. Although the forecasts do include the inner London Ultra-Low Emission Zone (ULEZ) expansion that took place in October 2021, they do not include the London-wide expansion across all London boroughs that occurred in August 2023. Although PM$_{10}$ from brake wear among total PM from road transport is declining in absolute terms from 1435t in 2013 to 1034t in 2030 due to lower brake emissions from electrified vehicles, it increases in relative terms in the same period from 62% to 73%. This is because exhaust emissions are reducing rapidly due to the increasing prevalence of electrified vehicles and conventional vehicles of the latest Euro standards which have a particulate filter. Unlike exhaust emissions, and to some extent brake emissions, tyre emissions (PM$_{10}$ and PM$_{2.5}$) are not decreasing over time. Instead, they are expected to remain steady or even increase in absolute terms. Specifically, PM$_{10}$ from tyre wear is predicted to have a small increase, from 16% in 2019 to 24% by the end of the decade. As for PM$_{2.5}$, the difference between the different sources from brake, tyre and exhaust emissions was much smaller. PM from road wear is excluded from London's road transport emissions calculations because the sources of particles are hard to distinguish from the resuspended particles from other sources. However, PM$_{10}$ from road dust resuspension and road wear cannot be ignored since they represent around 15% of total PM emissions as indicated in Figure 2.

Key finding #2.1: Today the majority of PM_{10} emissions from road transport in London come from brake wear. However, due to fleet electrification, brake wear and exhaust emissions are expected to decrease while tyre emissions are expected to increase because of the increased vehicle weight, if no further action is taken.

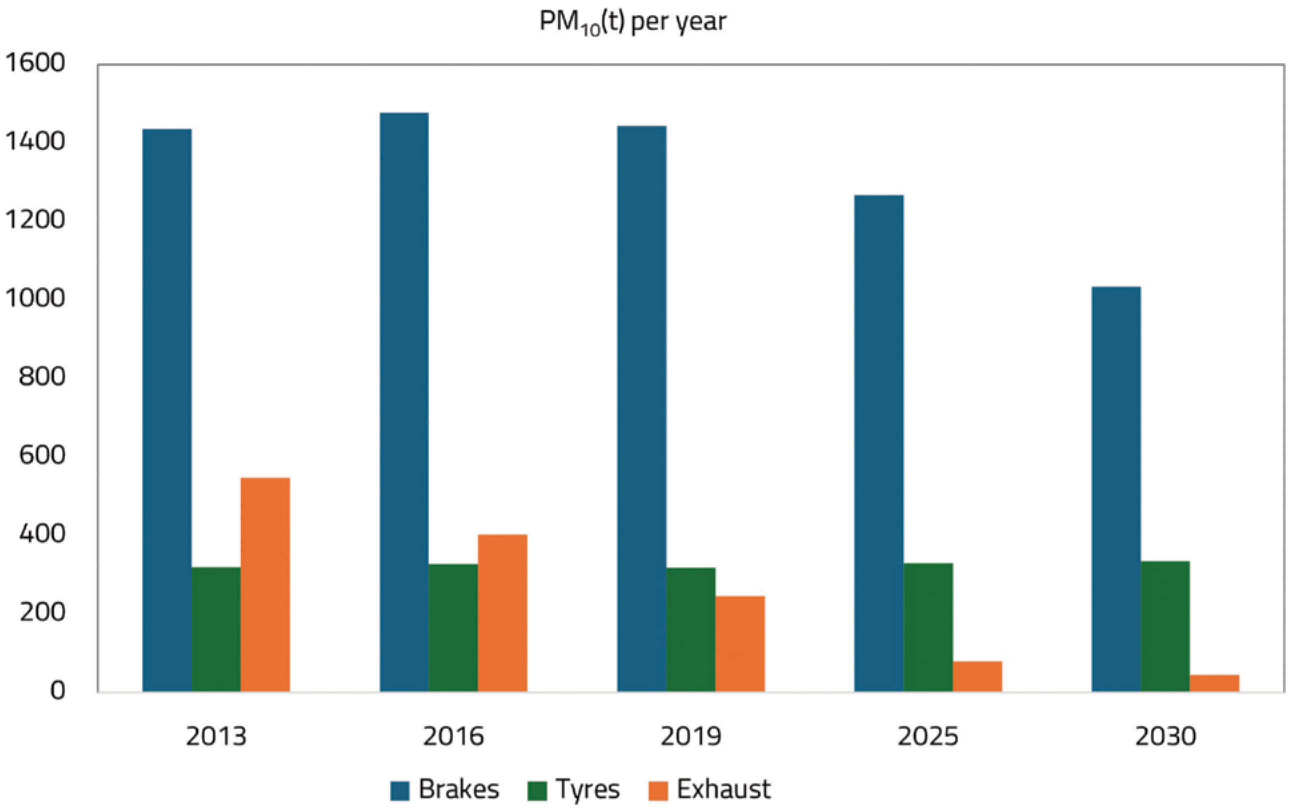


Figure 3: Breakdown of PM_{10} emissions from road transport by source in Greater London. Data from LAEI (2019).

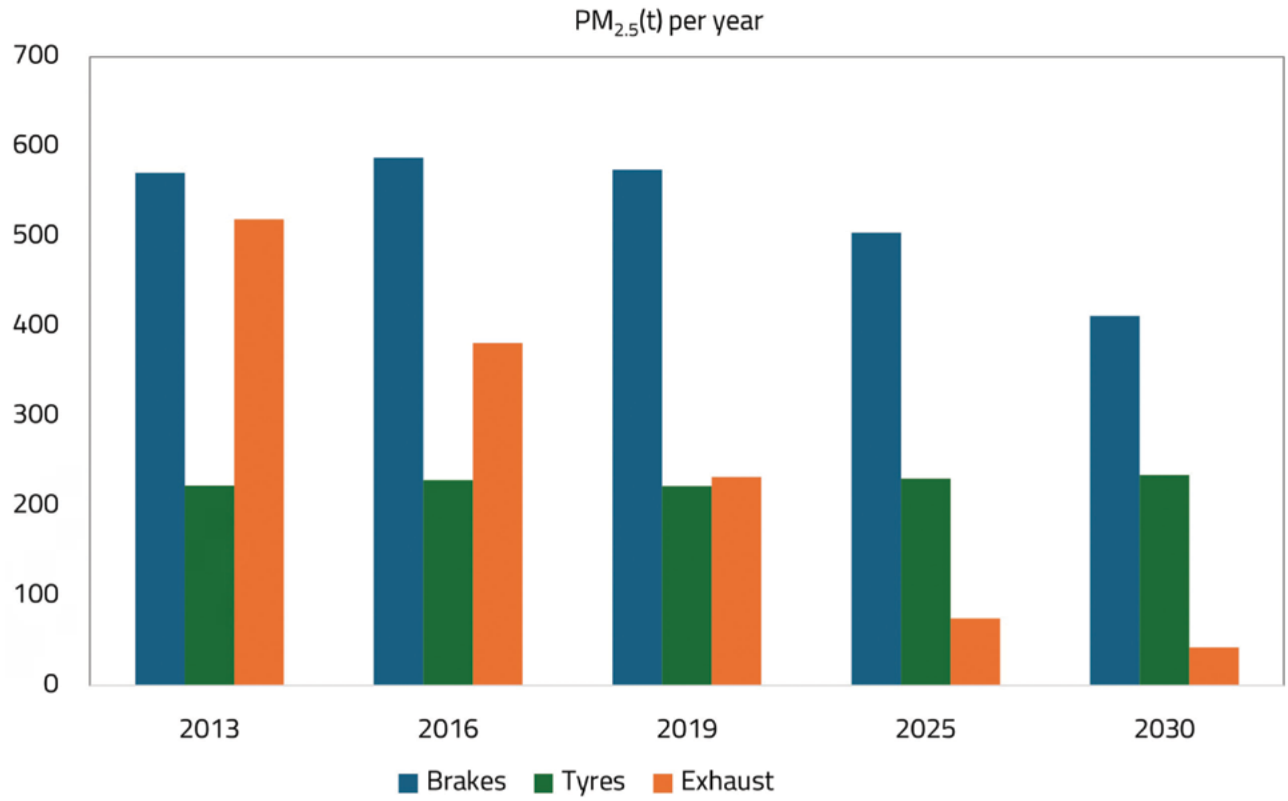


Figure 4: Breakdown of $PM_{2.5}$ emissions from road transport by source in Greater London. Data from LAEI (2019).

Figure 5 verifies that the conclusion of Figure 3 apply for all types of vehicles: In 2019, the majority of PM_{10} emissions from road transport in London originate from brake wear for all vehicle types and its share among total road transport PM_{10} emissions ranges from 57% for articulated heavy-good vehicles (HGVs) to 85% for TfL (Transport for London) buses.

For $PM_{2.5}$, brake wear still accounted for most of NEE from road transport, but its share is slightly less and ranges from 41% to 74% depending on the vehicle type and fuel, as illustrated in Figure 6.

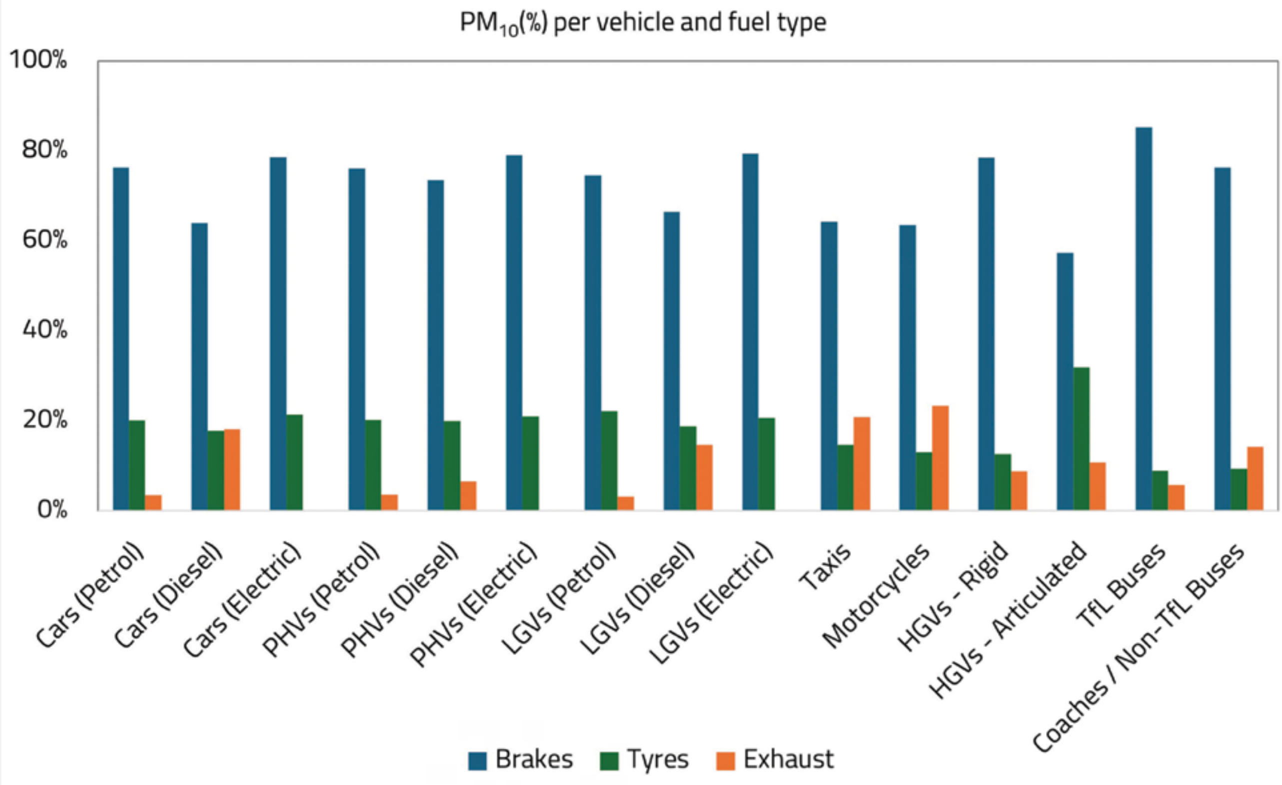


Figure 5: Breakdown of PM_{10} from road transport by source for each vehicle and fuel type in London in 2019. Data from LAEI (2019).

Figure 7 and Figure 8 indicate the relative PM_{10} and $PM_{2.5}$ emissions by source per kilometre driven for each type of vehicle compared to the weighted average vehicle value of year 2019. This relative difference is important because it shows the difference between light and heavy vehicles in terms of non-exhaust emissions (by source).

As expected, heavier vehicles, and especially buses that circulate mainly within the city and have stronger and more frequent braking and cornering events, so their brake and tyre emissions are well above the average values, while passenger cars are below the average values.

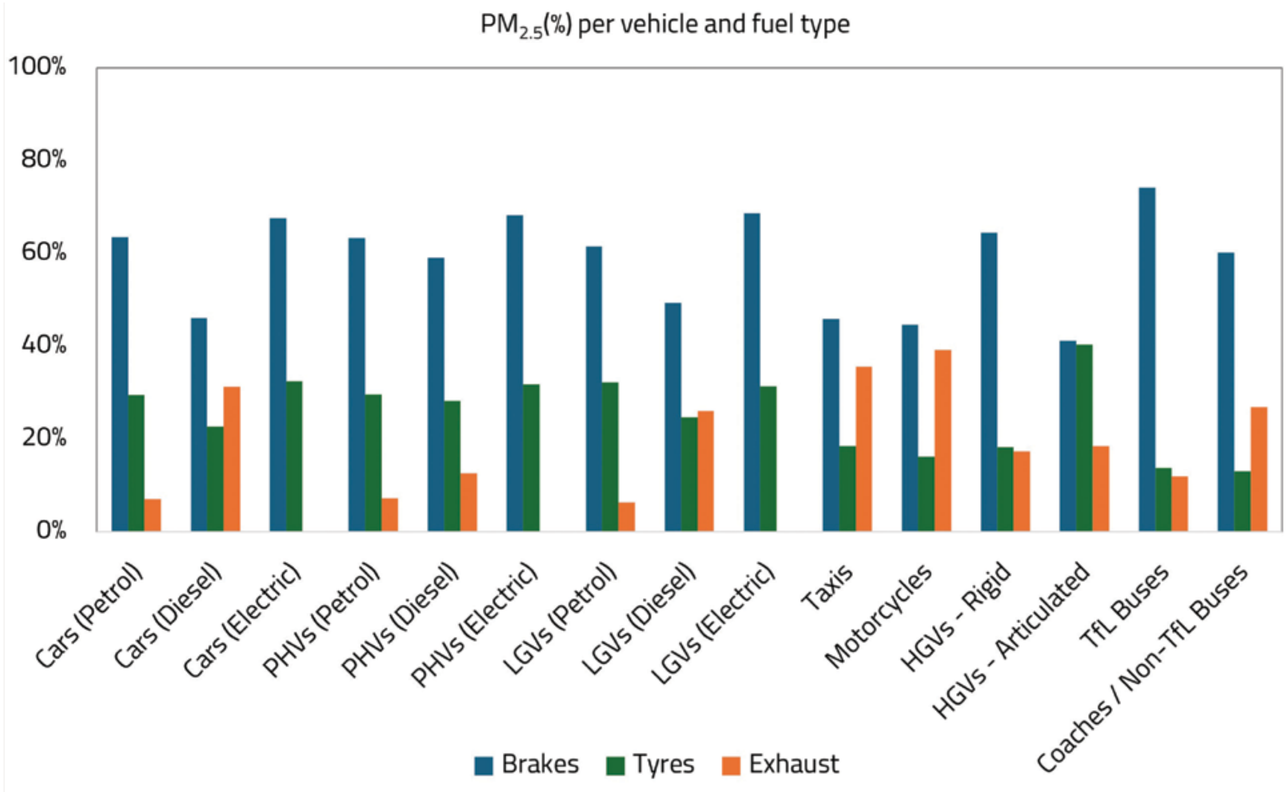


Figure 6: Breakdown of $PM_{2.5}$ from road transport by source for each vehicle and fuel type in London in 2019. Data from LAEI (2019).

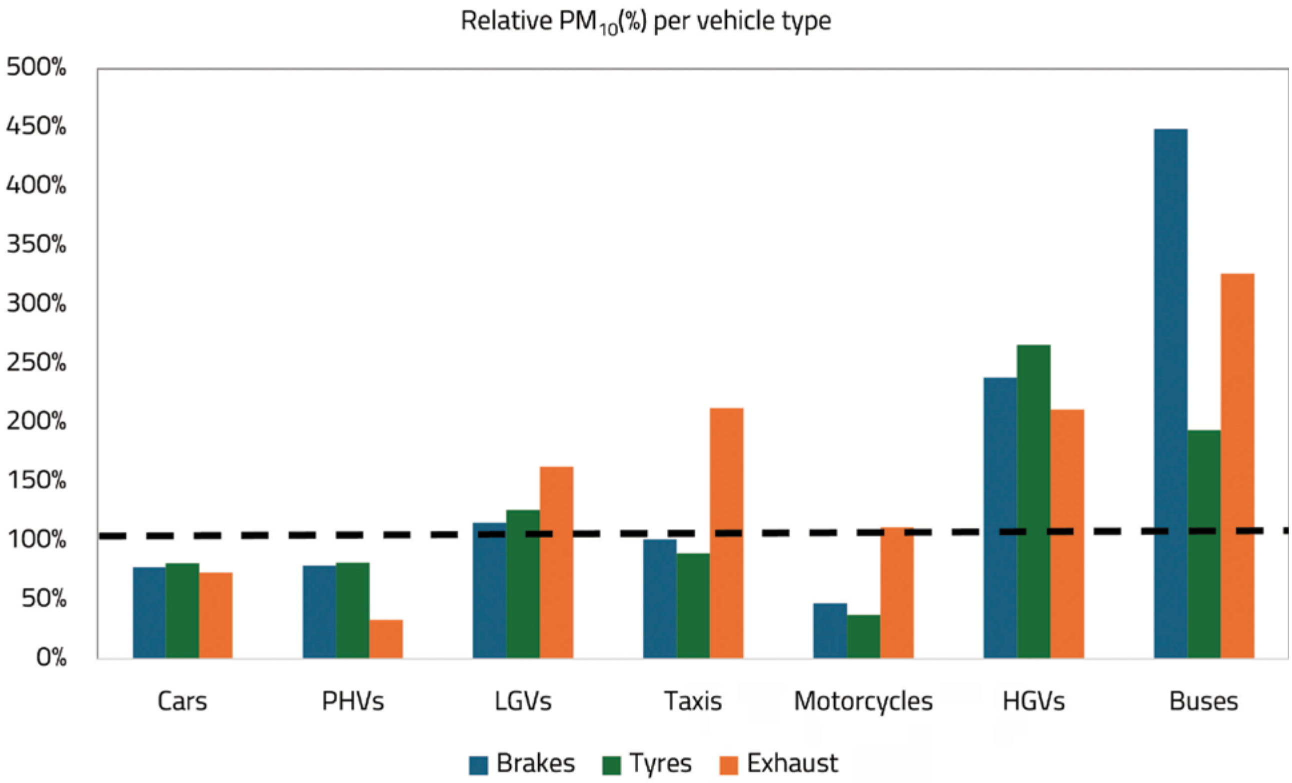


Figure 7: Relative PM_{10} emissions per kilometre by source for each vehicle in London in 2019. Data from LAEI (2019).

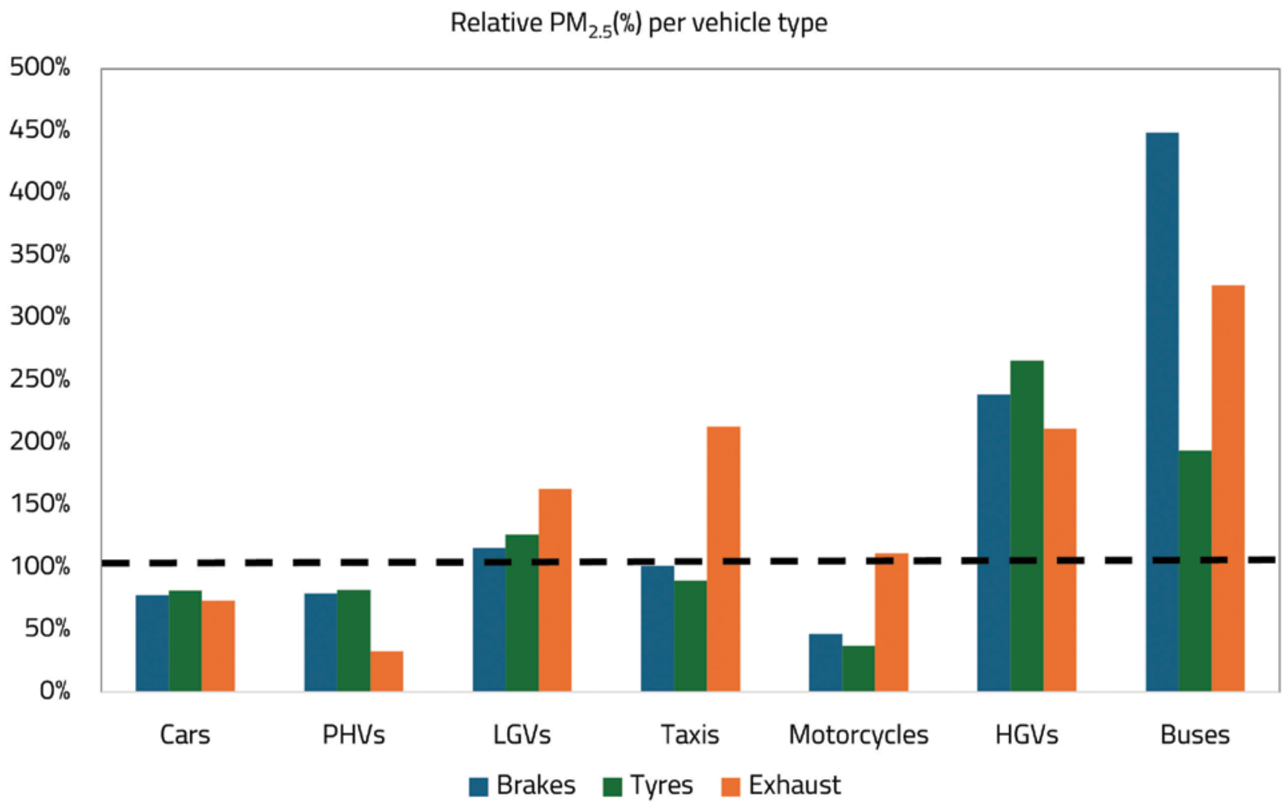


Figure 8: Relative $PM_{2.5}$ emissions per kilometre by source for each vehicle in London in 2019. Data from LAEI (2019).

Key finding #2.2: Heavy-duty vehicles emit 3 to 5 times more particles than passenger cars depending on the source. The value varies among the different sources of PM emissions and depends on the fleet electrification degree.

Fleet electrification has an impact not only on exhaust emissions but also on non-exhaust emissions. Fleet electrification eliminates exhaust emissions and reduces brake wear emissions, due to regenerative braking. However fleet electrification can lead to increased tyre and road wear emissions due to the increased vehicle weight.

Figure 9 and Figure 10 illustrate the projected evolution of the fuel mix in London for light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs), respectively, according to the London Atmospheric Emissions Inventory (LAEI) 2019 baseline. The percentages indicate the share of each fuel separately for each vehicle type for the years 2019, 2025 and 2030. By 2030, 42% of the LDVs' are expected to be battery electric, which is almost three times more than in 2025 and 100 times more than in 2019. Slower electrification is expected for HDVs since only 15% of the vehicles are expected to be electric by 2030 compared to 6% in 2025 and 0.2% in 2019.

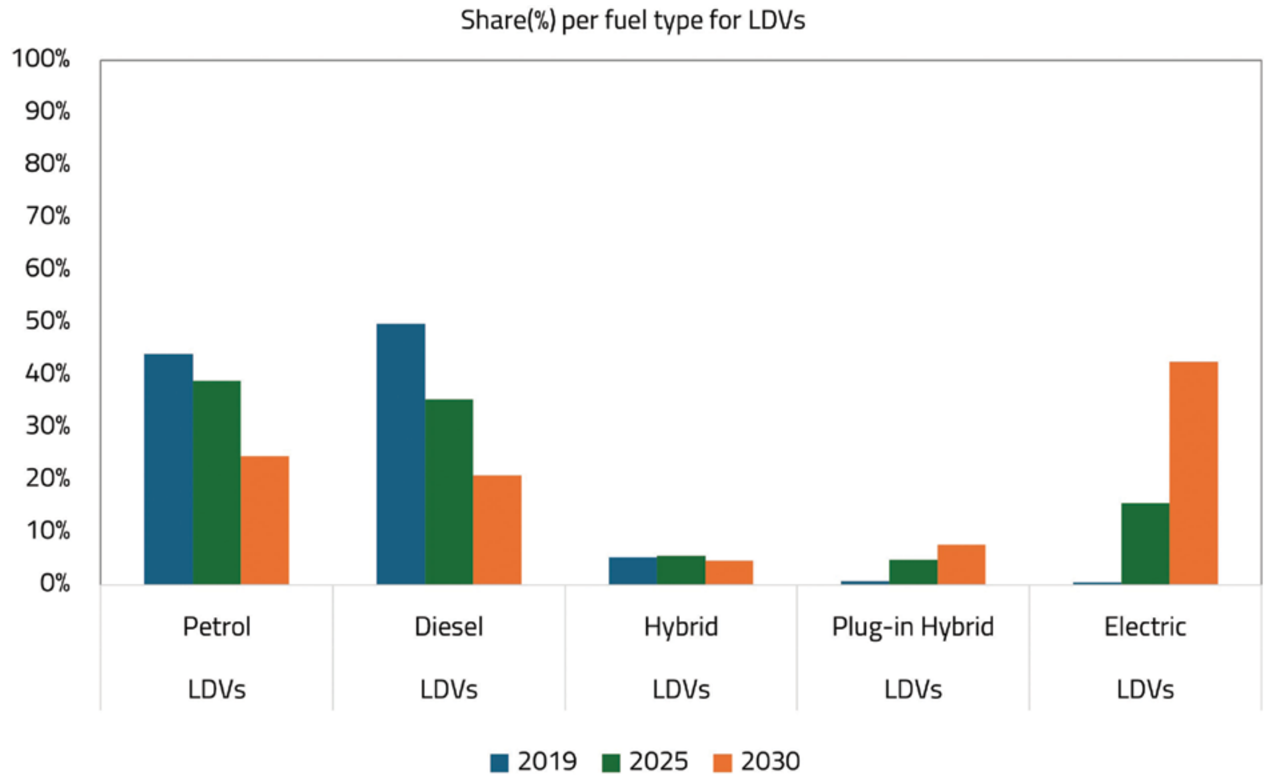


Figure 9: Projected fleet composition in London for the years 2019 (historical data), 2025 and 2030 for LDVs. Percentages give the share of each fuel. Data from LAEI (2019).

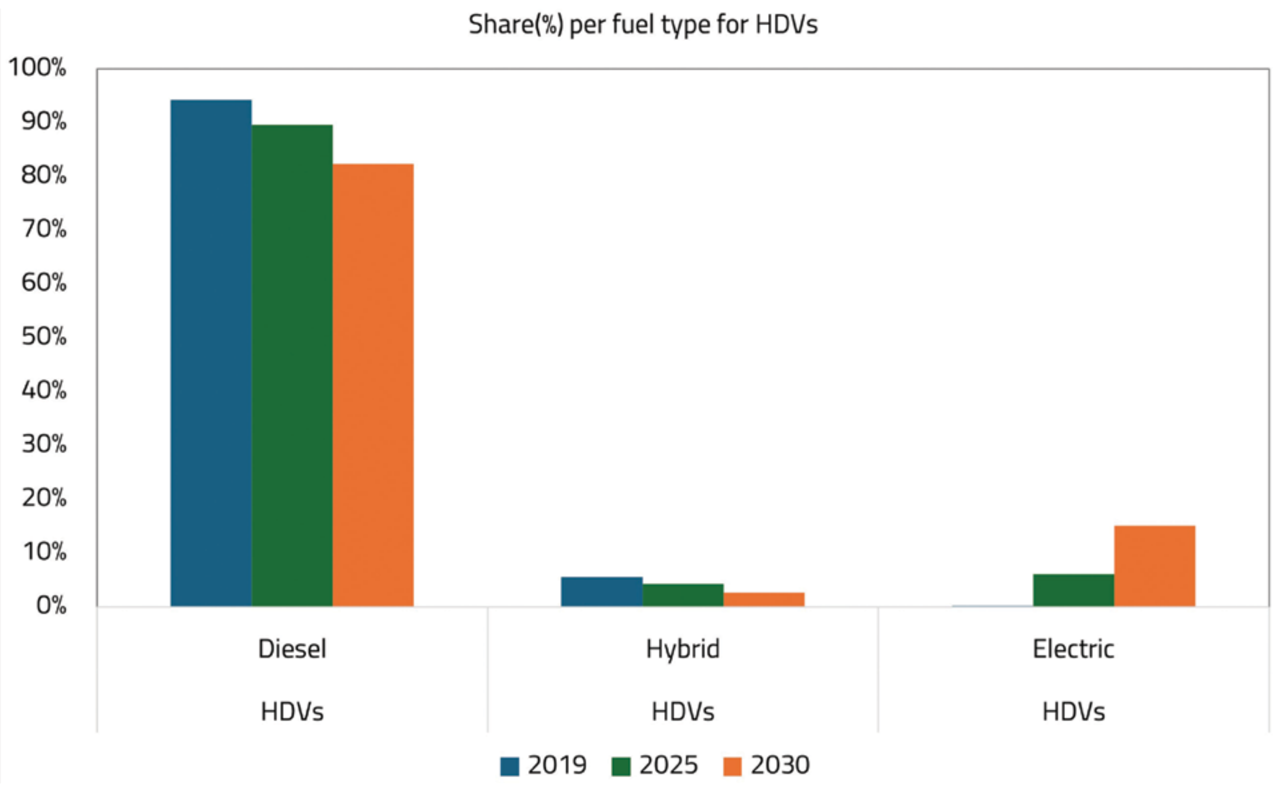


Figure 10: Projected fleet composition in London for the years 2019 (historical data), 2025, 2030 for HDVs. Percentages give the share of each fuel. Data from LAEI (2019).

As highlighted in Chapter 1, particles smaller than 2.5 microns ($PM_{2.5}$) are especially harmful to health due to their ability to penetrate deeply into the lungs and the blood stream [3]. The proportion of fine ($PM_{2.5}$) to coarse (PM_{10}) particles varies across different PM sources in road transport, based on data from the London Atmospheric Emissions Inventory (LAEI) and applicable to all vehicle types. For exhaust emissions, 95% of PM_{10} particles are fine ($PM_{2.5}$). 70% of the total particles from tyre wear are fine particles, while fine particles from brake wear consist only 40% of total brake wear particles, and the ones from road dust resuspension, including road wear, only 5%.

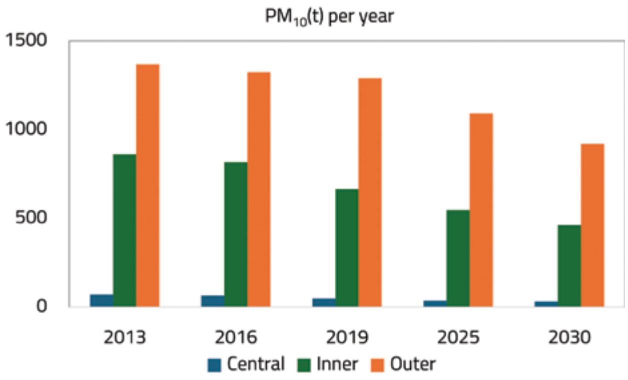
Key finding #2.3: While brake wear is the largest overall contributor to total particles, only 40% of them are fine particles (i.e. PM2.5), which are more harmful to health. For exhaust emissions, this ratio increases to 95%, while for tyres it is 70%.

Figure 11 shows the predictive trends in PM_{10} and $PM_{2.5}$ from road transport within Greater London. For the LAEI, Greater London is divided into three zones: central, inner and outer London. The central zone covers the Congestion Charge Zone, inner London is up to and including the North and South Circular roads while outer London covers the rest of London.

Between 2016 and 2019, $PM_{2.5}$ emissions from road transport were estimated to have decreased by 34% in central London, 24% in inner London, and only 7% in outer London, which contributes the most $PM_{2.5}$ emissions overall. Across Greater London, the reduction was 14%. PM_{10} reductions followed a similar pattern, with reductions of 24%, 19%, and 2% for central, inner, and outer London, respectively, and an overall reduction of 9%.

Looking ahead to 2030, projections indicate further declines in $PM_{2.5}$ emissions, with reductions of 40% in central London, 34% in inner London, and 32% in outer London compared to 2019 levels, resulting in a 33% reduction across Greater London. PM_{10} emissions are also expected to decrease by 35% in central London, 30% in inner London, and 29% in outer London, with an overall reduction of 29% across Greater London.

This decreasing trend is mainly due to the diminishing exhaust emissions as a result of the anticipated fleet electrification, the original central London ULEZ, the expansion of the ULEZ to inner London, the Mayor's policies on cleaner taxis, private hire vehicles and buses and other Mayoral initiatives that are described in the Annex. While the forecasts account for the inner London ULEZ expansion, they do not reflect the London-wide expansion to all boroughs implemented in August 2023, meaning the reductions in exhaust emissions across London should be greater than currently forecast [8].



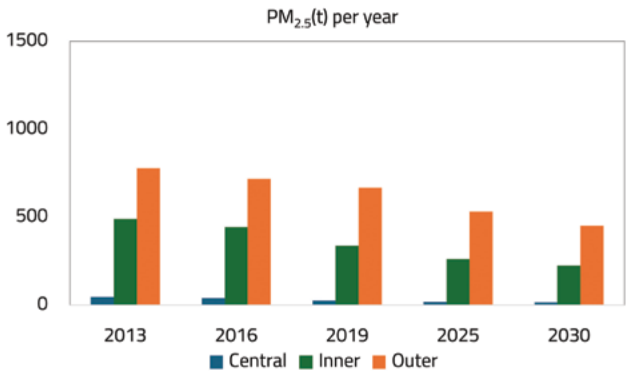


Figure 11: Evolution of PM from road transport among LAEI zones: (top) PM10; (bottom) PM2.5. Data from LAEI (2019).

> **Key finding #2.4:** Outer London covers a larger geographic area with more vehicle kilometres driven and contributes more to overall PM emissions of London.

The LAEI also provides data for the breakdown of PM_{10} and $PM_{2.5}$ by road type. Based on their traffic flow, all roads in London are classified as major or minor. Minor roads have lower emissions since they have lower traffic volumes. Around 87% of total PM from road transport in 2019 was emitted in the major roads of London. The majority of PM is from passenger cars since there are proportionally more cars compared to other vehicles.

2.2 Comparison with other cities

Most publicly available, official, sources of information for non-exhaust emissions from road transport for European cities, comparable to London, do not provide detailed data. They also most commonly do not examine brake, tyre, and road wear separately, while some others rely on national emission inventories for their calculations. Moreover, there are significant discrepancies in the way data are reported, thus making direct comparisons very difficult. We note that, in the context of this study, we consider as comparable, cities that are European metropoles or capitals, with densely populated urban areas, heavy traffic volumes and/or similar transport challenges to London, such as congestion and air pollution from the road transport sector. Barcelona and Milan are two cities for which some up-to-date, official data on non-exhaust emissions from road transport are available. Our findings are summarized in the following paragraphs. Some independent studies have also been performed for Stockholm, Paris, Berlin, and Lisbon, but there is a lot of information missing. The main findings of these studies are gathered in Table 6 of the Annex. Table 1 shows some general information on all the above cities' population, as well as their air quality based on $PM_{2.5}$ concentrations for years 2019-2021, as per the European Environment Agency (EEA) [14], [15].

> **Key finding #2.5:** Our research showed that there is limited data available from most European cities on non-exhaust emissions.

Table 1: Comparable cities to London; population and air quality based on $PM_{2.5}$ emissions [14], [15], [16].

City	Population	$PM_{2.5}$ annual average 2019-2021 (μg/m³)	Air quality
London	8,866,180	10.8	Moderate
Milan	3,622,641	20.2	Poor
Barcelona	3,755,512	13.7	Moderate
Stockholm	1,745,766	5.7	Fair
Paris	9,845,879	8.3	Fair
Berlin	3,669,491	12.2	Moderate
Lisbon	1,872,036	10.8	Moderate

Barcelona

In Barcelona, road transport is the sector with the second greatest contribution in PM pollution, following the port which accounts for more than half of the total particulate matter emissions. More specifically, road transport is responsible for 36% of PM_{10} and 29% of $PM_{2.5}$ emitted to the environment, annually. Although average PM emissions have been progressively decreasing since 2017, the latest update of Barcelona's Air Quality Guide reported that in many cases they still exceed the thresholds recommended by the World Health Organization (WHO) [17].

In 2021, 152t of PM_{10} and 96t of $PM_{2.5}$ were released from road transport, with as much as 118 t of PM_{10} and 62t of $PM_{2.5}$ attributed to NEE sources. Figure 12 and Figure 13 show the percent PM_{10} and $PM_{2.5}$ emissions, respectively, broken down by source, i.e., brakes, tyres, road, and exhaust, for each type of vehicle. Regarding fuel type, there is no official data available on the number of vehicles by category and fuel type [17].

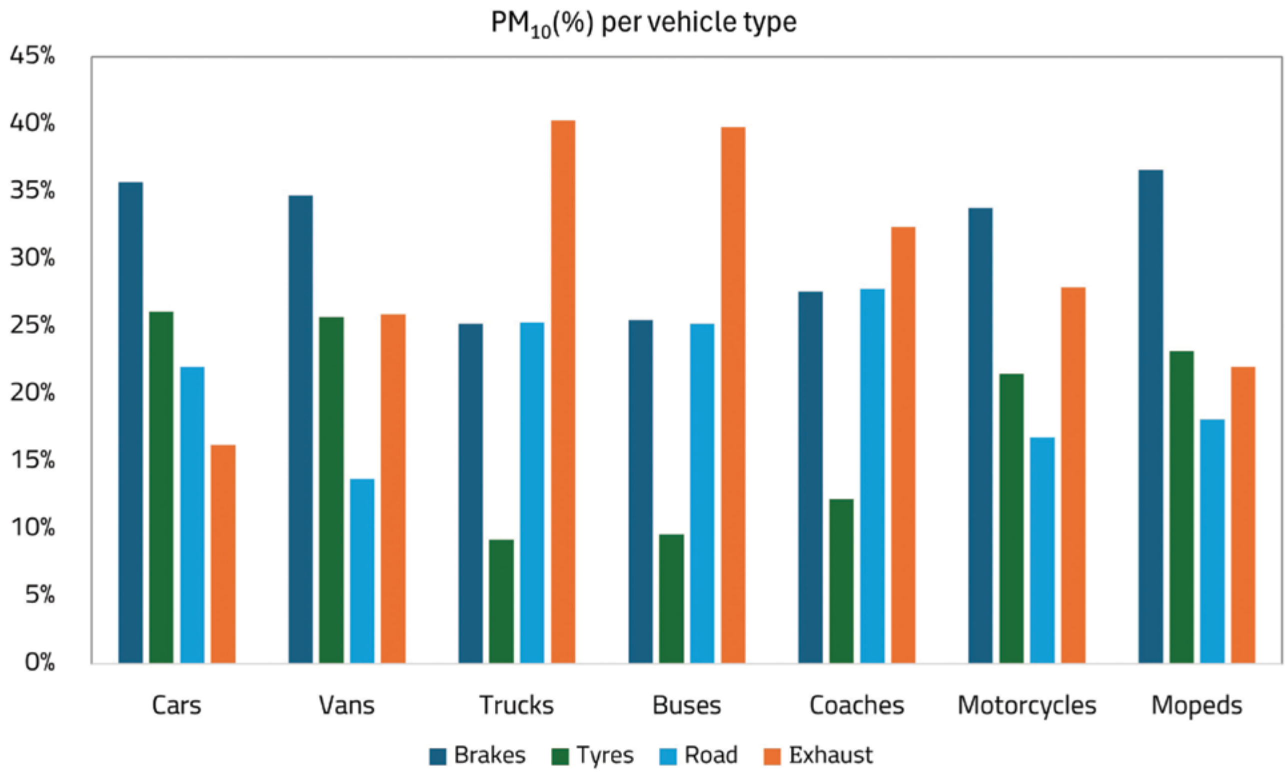


Figure 12: Breakdown of PM_{10} from road transport by source for each vehicle in Barcelona in 2021 [17].

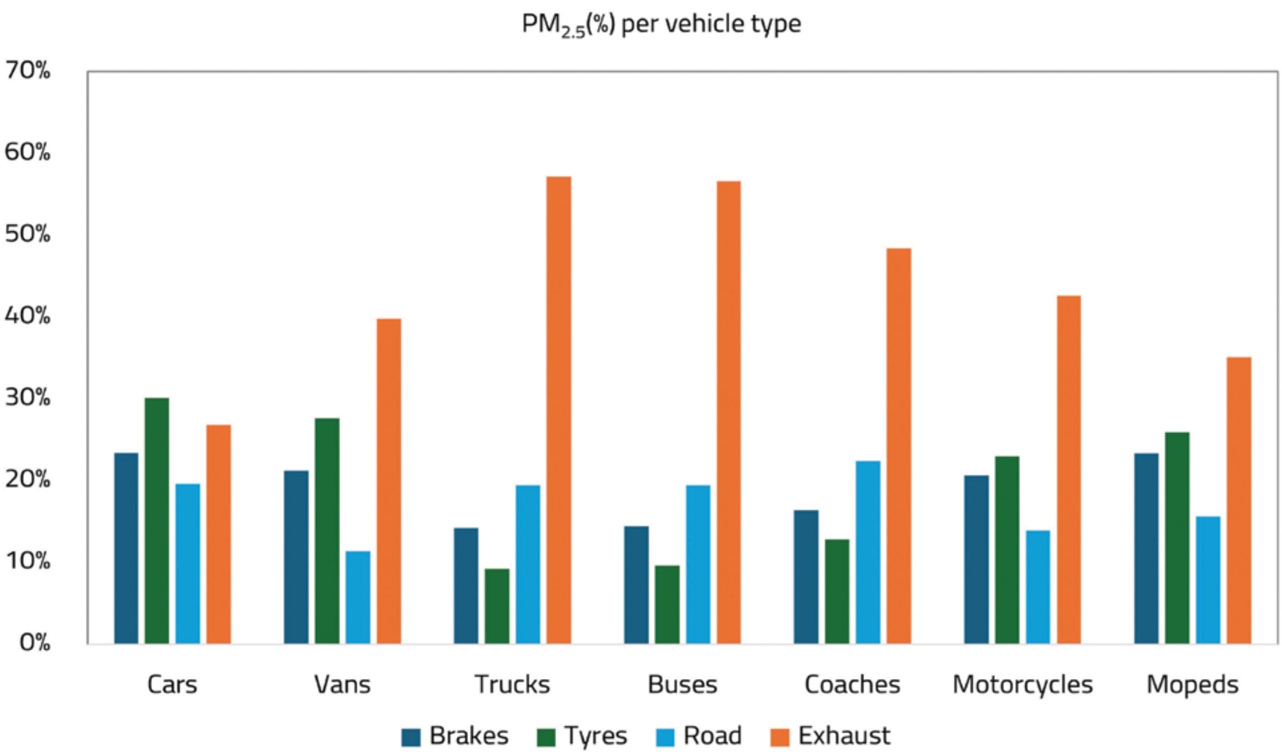


Figure 13: Breakdown of $PM_{2.5}$ from road transport by source for each vehicle in Barcelona in 2021 [17].

Key finding #2.6: NEEs are responsible for 78% of PM10 and 65% of PM2.5 emissions from road transport in Barcelona. Similar to London, for passenger cars, PM10 emissions are dominated by brake wear. However, for HDVs exhaust emissions are the main contributor among all sources (brake, tyre, road wear and exhaust) both for PM10 and PM2.5 emissions but in all cases, they remained below 40%. In LDVs, PM2.5 is almost equally distributed among the different sources.

Barcelona has a Low Emission Zone (LEZ) in place, targeting only exhaust emissions from internal combustion engine (ICE) vehicles, as well as an additional, emergency LEZ which includes extra or stricter restrictions and is activated when pollution levels of PM_{10} and NO_2 exceed the designated thresholds. Another initiative of the Spanish capital against road transport pollution is the establishment of "superblocks", i.e., the grouping of several city blocks (typically 9) and the restriction of traffic within them. Cars are allowed to enter the city blocks at low speeds and drive around them, but not through them. In this way, the streets inside superblocks are dedicated to active and public transportation, with the added benefit of reduced local air pollution and noise [18].

Milan

Milan's air quality is relatively poor, with higher concentrations of particulate matter observed compared to the other cities (see Table 1). Milan has low emission zones in place, but all of them are targeting the reduction of exhaust emissions and only indirectly influence NEEs (e.g. less vehicle kilometres travelled by conventional vehicles within Milan and promoting public transport) [19]. As per the Italian Emission Inventory (INEMAR) the levels of PM pollution from road transport are 2 to 5 times greater in urban roads (which the present report focuses on) than rural roads and highways, for almost all vehicles except heavy-duty trucks which circulate outside the city [20].

According to Lombardy's Regional Agency for Environmental Protection (ARPA Lombardia) [21], road transport is Milan's main contributor to PM emissions. More specifically, only in 2021, 2,263t of PM_{10} were emitted, from which about 1,018t (or c.45%) were attributed to road transport. Similarly, road transport was responsible for 38% of a total of 1,816t of $PM_{2.5}$ produced in the same year [22]. Furthermore, about 30% and 20% of the total PM_{10} and $PM_{2.5}$ emissions, respectively, were linked to non-exhaust sources [22], [23], although there are no data available to further breakdown the percentage contribution of each source, i.e., brake, tyre, and road wear. This means that total NEEs account for about 68% and 53% of road-transport PM_{10} and $PM_{2.5}$, respectively. Figure 14 compares the share of NEEs in road transport emissions in Milan (for year) 2021 to the ones in London 2019 and Barcelona 2021.

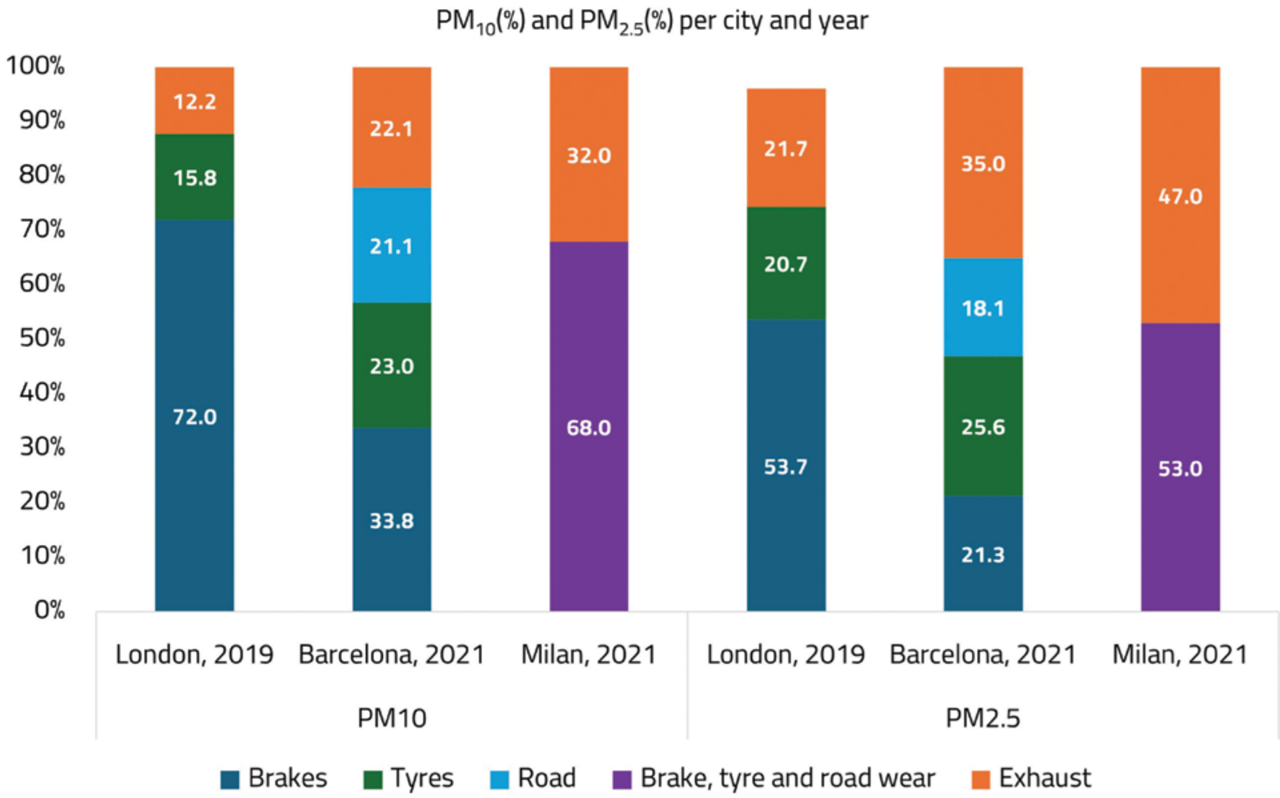


Figure 14: Percentage of PM_{10} and $PM_{2.5}$ road transport emissions by source in London 2019, Barcelona 2021, and Milan 2021. Road wear is not included under road transport in the case of London (see also Section 2.1). The breakdown of NEE into brake, tyre and road wear for Milan is not available.

Key finding #2.7: NEEs (brake, tyre and road wear) exceed exhaust PM emissions from road transport in all three cities of London, Barcelona and Milan. Exhaust emissions have a larger contribution in Milan reaching 32% and 47% of PM10 and PM2.5 emissions respectively while the corresponding percentages are 12% and 22% in London (less than half of those of Milan) and 22% and 35% in Barcelona.

Non-exhaust emissions from road transport are a dominant contributor to PM pollution in urban areas like London, where brake wear accounts for the majority of PM_{10} (and $PM_{2.5}$) emissions across all vehicle types. Fleet electrification reduces exhaust emissions but has a more limited impact on non-exhaust sources since it reduces brake wear but increases tyre and road wear emissions. A comparison with cities like Barcelona and Milan underscores the variability in data availability and intervention strategies, emphasising the need for consistent monitoring and targeted policies to address NEE effectively.

3 Key factors affecting non-exhaust emissions

Reducing non-exhaust emissions (NEEs) is an urgent matter that requires addressing all individual sources. Before examining interventions tackling each source of NEE, a comprehensive understanding of the characteristics and the factors influencing NEEs is needed, which is the focus of this chapter.

3.1 Emission Factors: Definition and Importance

During the period 2017-2021, average PM_{10} emissions from non-exhaust sources of the road transport sector in the European Union (EU) were found to be 112,000t, with 59,000 of them being $PM_{2.5}$, based on a study conducted on behalf of the European Commission [24].

For the same period in the United Kingdom (UK) average PM_{10} and $PM_{2.5}$ emissions from road transport reported in its inventories, were 18,000t and 9,000t, respectively, utilizing data from COPERT [25]. The percentage contributions of each NEE source for the EU and UK are given in Figure 15 [26].

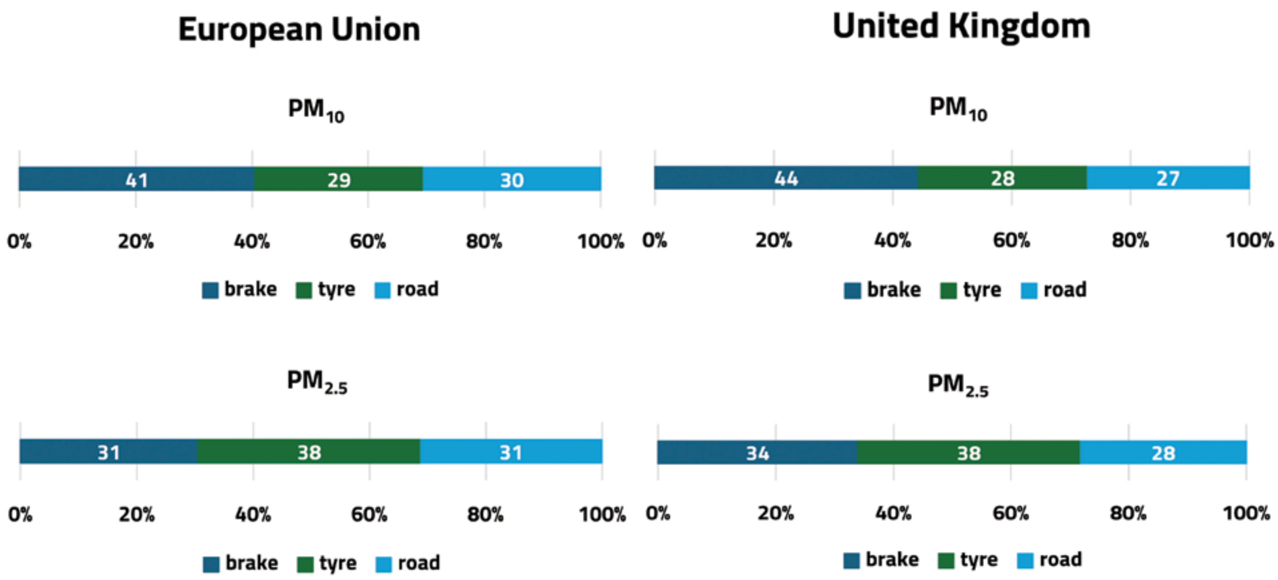


Figure 15: Contribution of each source (brake, tyre, road wear) to total NEEs from road transport for years 2017-2021 in the European Union (left) and the United Kingdom (right).

Although in both the EU and UK, all sources clearly contribute significantly to total non-exhaust emissions (NEEs), the individual contributions are different for each region. For example, the contribution of tyre wear emissions to $PM_{2.5}$ are reported higher in the EU and UK (Figure 15) compared to the ones in London (Figure 4). This can largely be explained by the fact that each country has its own vehicle fleet and activity and that NEEs are affected by multiple parameters. To effectively assess the severity of PM pollution and estimate the pollution reduction potential of mitigating measures, we need first to evaluate the contribution of each source to it and make fair comparisons between different regions. Emissions need to be expressed in a common, normalised unit that correlates their amount to the activity that produces them. Therefore:

Key finding #3.1: Most countries have adopted the use of coefficients, known as emission factors, that express emissions per kilometre, for their official inventories.

However, there are still limited measurement data regarding NEEs and many knowledge gaps exist, therefore there is a great deviation of emission factors among regions. Another essential input to the inventories is the fleet data, which allows further specification of emissions, e.g. depending on the type or fuel of the vehicle.

Ultimately, the most useful information is given when emission factors are expressed in mass per distance per vehicle (e.g. mg/km/veh). It is noted that emission factors pertain to both the total mass (Particle Mass – PM) and the total number (Particle Number – PN) of particles emitted.

Emission factors can be directly deduced from laboratory and on-road measurements, or they can be acquired indirectly through receptor modelling. Due to the multiple factors that affect each source (analysed in the following sections), as well as the variety of sampling and measurement protocols and the lack of standardised methodologies [with the exception of the Global Technical Regulation (GTR24) methodology for brake wear of light-duty vehicles (LDVs) analysed in Chapter 5], there are often large discrepancies among the reported PM emission factors. Nevertheless, it is important to have the most recent, up-to-date data available and, therefore, a thorough literature review has been performed in the context of this study, to acquire the Emission Factors (EFs) for brake, tyre, and road wear for light-duty vehicles (LDVs), that will be used in the analysis performed in the following chapters. For heavy-duty vehicles (HDVs), there is a knowledge gap since no standardised methodology exists yet, and most studies rely on outdated data or extrapolations based on LDVs. The main findings of the review are summarised in Table 2, and they are discussed in more detail in the following sections.

Regarding the variability of the emission factors presented in the following paragraphs and used in the analysis and modelling of the scenarios, we note that this can only be quantified (in the form of standard deviation) in the case of brake wear, and only using the studies that follow the standardised GTR24 methodology and examine a specific type of brake friction pair (grey cast iron disc with low-metallic or semi-metallic pads – see also Section 3.2). In the case of tyre and road wear emission factors, the measurement methods and conditions across studies vary significantly and standard deviation is not reported since it would mainly reflect methodological inconsistencies rather than real variability in emissions.

Table 2: Emission factors (EFs) for light-duty vehicles (LDVs) and data variability based on literature. Detailed findings are presented in Table 9, Table 10, Table 11 of Annex.

NEE source	Total studies examined	Percentage of recent studies examined (<5 years)	EF for LDVs	Data variability
Brake wear	35 indep-endents, 1 review	81 %	From studies based on GTR24 compliant methodologies: • PM_{10}: 13.2 mg/km/veh • $PM_{2.5}$: 5.3 mg/km/veh • PN: $9x10^9$/km/veh	Standard deviation: • PM_{10}: 5.3 mg/km/veh • $PM_{2.5}$: 2.3 mg/km/veh • PN: $8.6x10^9$/km/veh
Tyre wear	20 indep-endents, 3 reviews	70 %	• PM_{10}: 3.6 mg/km/veh • $PM_{2.5}$: 1.5 mg/km/veh • PN: $4x10^{10}$/km/veh	High variability, 4 orders of magnitude: Different methods and lack of standardized methodologies.
Road wear	10 indep-endents, 2 reviews	50 %	Different methods & lack of standardized methodologies: • PM_{10}: 3-40 mg/km/veh	High variability, 4 orders of magnitude: Different methods and lack of standardized methodologies.

3.2 Brake wear emissions

Brake wear takes place during a braking event due to the mechanical abrasion (the wear of a material's surface due to friction or contact with another surface) and thermal fatigue (the wear of a material due to repeated temperature changes) of the braking system surfaces that are in direct contact. Therefore, it is a particularly important source of pollution in urban areas, especially at so-called traffic "hot spots", such as road junctions, pedestrian crossings, traffic lights etc., where vehicles frequently slow down or stop.

Depending on their size, brake wear particles are dispersed in the environment and may either become airborne (suspended in the air) or sedimentary (deposited on various surfaces). More specifically:

Key finding #3.2: Recent research shows that around 40-45 % of brake wear particles produced during a braking event are suspended into the air as PM10 or finer (approximately 35-45% of PM10 from brake wear is PM2.5) particles [27]. The rest are deposited on surrounding surfaces such as the ground, roads, brake components, or the wheels.

Particles that are deposited on road surfaces have the potential to be washed away by rain or surface water. This runoff can carry particles into nearby water sources, such as rivers, streams, or drainage systems, contributing to water pollution and potentially impacting aquatic ecosystems.

The harmful impact of brake wear pollution is proportional to the total amount of particles released (mass and number), as well as its specific composition and characteristics, which in turn can vary greatly, depending on multiple parameters. For example, brake emissions from heavy-duty vehicles are one order of magnitude higher in congested than non-congested motorways. Literature review revealed that:

Key finding #3.3: The most important factors affecting brake wear are the braking system and vehicle characteristics, the driving behaviour (e.g. frequency and extent of braking), the environmental conditions (e.g. temperature and humidity) and the traffic flow.

There are two widespread types of braking systems in road transport: disc and drum brakes. Disc brakes are the most popular choice in Europe, especially for the front wheels of cars, whereas drum brakes are more often used on the rear wheels. It is reported that drum systems account for about 10% of the European brake market [28]. Although disc brakes exhibit a higher braking performance than drum brakes, especially under extreme environmental conditions, they are also associated with higher emissions [29]. Recent research has shown that:

Key finding #3.4: Drum brakes (currently used only for rear wheels) produce around 23% less wear than the most popular disc brakes [28]. Therefore, drum brakes are attracting more interest from the industry as an alternative braking system.

The two braking systems' operation, as well as the main components they are made up from, are briefly discussed in **Box 1**. The materials these components are made up from directly affect the amount, composition and physicochemical properties of the wear waste suspended in the air. Although the list of materials used for braking systems is extensive, the literature shows that grey cast iron (GCI) discs and low-steel (LS) brake pads are the most popular choices for European cars.

More specifically, grey cast iron (GCI) has been and still is the most popular and common material of choice for the manufacture of brake discs due to its excellent thermophysical properties and low cost, but it suffers from heavy weight and is very susceptible to wear. Therefore, research and the market are pushed towards solutions to enhance GCI's corrosion resistance (ability to withstand damage caused by chemicals, moisture or air, without rusting or degrading) by applying hard-metal coatings (layers of metal such as tungsten carbide, cobalt and chromium) or replacing it with alternative materials, including steel, aluminium alloys, and carbon-ceramic composites. To this end, the following reduction potentials in particulate matter (PM), including both PM_{10} and $PM_{2.5}$, as well as particle number (PN) have been reported:

Key finding #3.5: Replacing grey cast iron (GCI) discs with carbon-ceramic composite discs reduces PM10 by 81%, PM2.5 by 74% and PN by 61% on average [28]. Alternatively, the application of hard-metal coatings on GCI reduces PM10 by 57%, PM2.5 by 60% and PN by 57% on average [28].

On the downside, such solutions are usually costly, and mass implementation would require the development of special, compatible pads. Since brake wear emissions were not regulated in the world until recently, their application is still quite limited and mostly concerns luxury vehicles and high-performance sports cars. This stands both for conventional and electric vehicles.

Brake pads are usually categorised depending on the material of their friction layer. The typical materials used in brake friction layers can be found in Table 7 of the Annex. The most popular choices in Europe are low-steel (LS) or low-metallic (LM) pads, often referred to as Economic Commission for Europe (ECE) pads. The typical formulation of LM pads is given in Table 8 of the Annex. Outside Europe, ceramic pads or non-asbestos organic (NAO) pads are more common, with the latter exhibiting promising results in terms of reducing brake wear emissions:

Key finding #3.6: Replacement of low-steel (LS) with non-asbestos organic (NAO) pads can reduce brake wear PM10 by 62%, PM2.5 by 55%, and PN by 64% [28].

Box 1: Braking systems and brake wear formation

Disc and drum brakes both operate on the principle of friction between the disc or drum (also known as the rotor part) and the braking pads or shoes. Specifically, during a braking event, particles are emitted into the air, produced by the friction between the so-called ‘friction pairs or couples’: the disc and friction layer of the pad in the case of a disc brake, and the drum and friction layer of the shoe in the case of drum brakes. A schematic representation of the main components and operation of the two systems is shown in Figure 16.

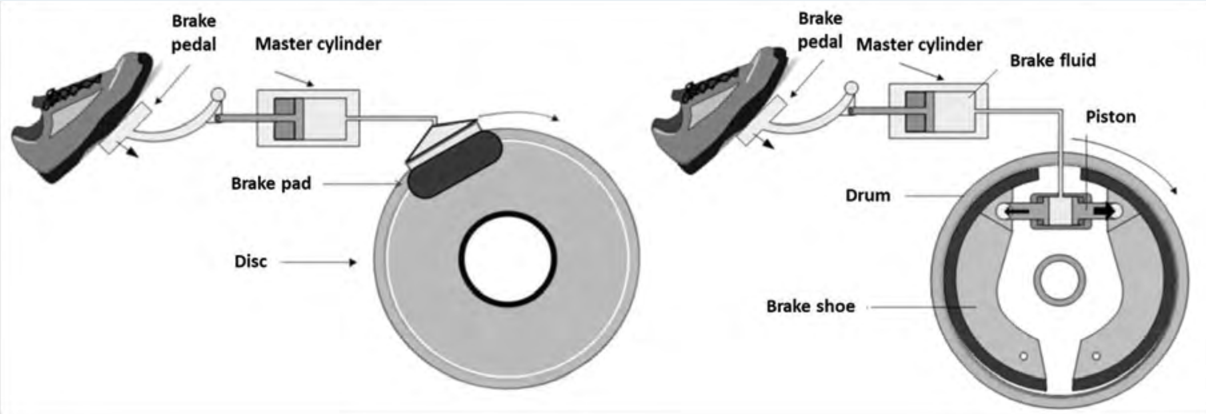


Figure 16: Components and operation of a disc (left) and drum (right) brake [10].

Although non-asbestos organic (NAO) brake pads offer substantial benefits in reducing brake wear emissions, their application is largely region dependent. While they are already widespread in the USA, Japan, and Korea, their penetration into the European market is still limited. From the bilateral discussions that have been performed with industry during this study, their main concerns regard performance requirements and their higher cost compared to low-steel brake pads.

Research on vehicle characteristics shows that age, mileage and application of brake cooling methods might have a small impact on brake wear, whereas the weight and powertrain of the vehicle appear to considerably affect brake wear emissions. As the weight of the vehicle increases, so does the braking force, resulting in greater wear of the braking system and increased PM emissions. The relationship between weight and PM emissions is complex and depends heavily on the disc and pad materials. For specific friction couples (see Box 1) however, it has been found that as the weight of the vehicle increases, so do its emissions in an almost linear correlation:

Key finding #3.7: A conventional car equipped with a grey cast iron (GCI) disc and low-steel (LS) pads emits on average about 8.8 mg of PM_{10}, 3.6 mg of $PM_{2.5}$ and 6 billion particles (PN) from brake wear per kilometre and vehicle tonne [28].

Electric vehicles are generally heavier than vehicles of the same class with equivalent sized internal combustion engines due to their battery packs. This increases braking demands and could lead to higher particulate matter (PM) emissions. However, regenerative braking, which recaptures kinetic energy from braking to recharge the battery, reduces reliance on traditional brakes, helping to lessen both brake wear and PM emissions. The overall impact of electrified vehicles on PM emission from brake wear depends on multiple parameters and the literature data indicate high discrepancy which comes from the different share of braking without using the mechanical brakes that can be found among the different lab and real-world measurements. Recent measurements, which are also adopted by the Global Technical Regulation at international level (more details provided in section 5.1), conclude that:

Key finding #3.8: As the level of electrification of a vehicle rises, the dependence on regenerative braking also increases, thus lowering PM emissions from brake wear. Based on recent evidence [30], regenerative braking can reduce, in the worst-case scenario (i.e. highest usage of mechanical brakes or equivalently lowest usage of regenerative braking), brake wear emissions by 10-48% for hybrid electric vehicles (HEVs), 66% for plug-in hybrid electric vehicles (PHEVs), and 83% for battery electric vehicles (BEVs).

Brake wear emission factors (EFs) can be directly acquired either by laboratory (brake/ chassis dynamometer or pin-on-disc) or on-road measurements. In a 2024 study [28], the authors performed an extensive literature review on measurements of light-duty vehicles' (LDVs') EFs based on the standardised Global Technical Regulation (GTR24) methodology (see also Chapter 5). The findings from this study were combined with average EU fleet data in another study, concluding that:

Key finding #3.9: The average brake wear emission factors of European passenger cars are estimated to be 13.2 mg/km/veh for PM10, 5.3 mg/km/ veh for PM2.5 and 9x109/km/veh for PN10 [28].

Similar values have been found in the literature review performed in the context of the present study, as most literature sources are common. The PM emission factors considered for this review are presented in detail in Table 9 of the Annex.

These values are close to the emission factors provided in the European Environment Agency (EEA) emission inventory Guidebook [31] and COPERT [25] which is used by most European countries for emission inventories. The brake emission factors are provided as a function of speed (EEA, 2024). The average PM_{10} values vary from 3.5 mg/km/veh for electric vehicles to 12.2 mg/km/veh for conventional vehicles while for $PM_{2.5}$ they are ranging between 1.4 mg/km/veh and 4.9 mg/km/veh correspondingly. The UK national inventory also follows the same methodology with COPERT and results on average are 13 mg/km/veh for PM_{10} and 5.2 mg/km/veh for $PM_{2.5}$ after adjustments to the UK's fleet data [32], which reflects the entire vehicle fleet with electric vehicles comprising only a small share (~3-4%).

3.3 Tyre wear emissions

Tyre wear particle emissions are the result of tyre abrasion due to shear and friction forces during steering, braking, and acceleration, as well as volatilisation (i.e. the evaporation of certain tyre components at higher temperatures). Besides particulate matter, tyre wear is one of the most significant sources of microplastics among all sectors, responsible for more than 35% of all microplastics emissions sources, with some studies claiming it can reach up to 93% [13], [33], [34], [35]. Over the course of its service life, which is approximately 40,000 km [13], a passenger car's tyre loses approximately 10 % of its total mass, which translates to 0.6–1.5 kg for a typical tyre weight of 7–12 kg [13]. Therefore, this means that:

Key finding #3.10: It is estimated that around eight thousand tons of tyre wear material is released annually in London alone. However, only 2-5% of total tyre wear becomes airborne, 40% of which is PM2.5, whilst 95-97% ends up on the roadsides, with a considerable part ultimately being dispersed in soil and water [36], [37], [13].

Box 2 illustrates an overview of the generation of tyre particles and how they are transported into the environment. The amount and characteristics of tyre wear depend on multiple parameters.

Key finding #3.11: The amount and the composition of tyre wear particles are highly influenced by the tyre, vehicle and road characteristics, as well as the driving and environmental conditions.

The type, size, material, tread depth, and pressure of a tyre are all factors that affect its wear. For example, preliminary data from a recent study on taxis with internal combustion engines revealed that summer tyres were associated with emissions of 53 mg/km/veh, all-season tyres with 112 mg/km/veh, and winter tyres with 160 mg/km/veh. Considerable emission variations between winter and summer were further supported by another study [38], but when many tyres are taken into consideration the differences appear to be more subtle [39]. Therefore:

Key finding #3.12: Preliminary data indicated that abrasion rates associated with winter tyres can be up to three times higher than summer tyres, but recent studies that gathered measurement data from many tyres, concluded that the differences are much smaller and between 5-23% [13], [40]. Moreover, studded tyres, often used in northern European countries in winter, emit much more emissions than un-studded tyres [41].

On the other hand, the weight, mileage and suspension system of a vehicle have a significant impact on tyre wear, as well. More specifically, vehicle weight appears to be a particularly important factor in the abrasion rate, with studies reporting that:

Key finding #3.13: Vehicle weight is directly proportional to tyre wear emissions. For example, a car with a 20% higher mass demonstrated a 20% increase in tyre wear [13]. Electric cars are around 20% heavier than the equivalent conventional cars, so they emit around 20% more tyre wear [40], [42], [43].

PM emissions from tyres also depend heavily on driving behaviour; aggressive manoeuvres, such as sudden acceleration, braking, and steering, lead to significant increases in tyre abrasion due to higher tangential forces. This type of driving is more common in urban environments, therefore:

Key finding #3.14: Tyre wear emissions are more prominent in urban roads compared to rural roads or motorways due to more often cornering and acceleration/deceleration events. A recent study has shown that abrasion rates are about 1.9-5.4 higher in urban environments [44].

Other parameters that affect tyre wear emissions include road surface properties such as material, porosity, and condition. Generally, the rougher the road surface, the higher the friction coefficients, leading to increased tyre abrasion.

Box 2: Tyre wear sources and dispersion

As shown in Figure 17, the primary source of tyre wear is the abrasion between the tyre tread and road surface. Particulate matter is also formed through volatilization, i.e. the evaporation of certain tyre components at higher temperatures. Once produced, particulate matter may follow several pathways into the environment, as indicated by the arrows:

- **Direct release to air:** Most commonly, about 2-5% of tyre wear particles become airborne, and can enter the human body through inhalation, ingestion, or skin absorption or it may be transported over long distances, ending up contaminating the soil and water ecosystems.
- **Deposition on and near the road:** Up to 75% of tyre wear is deposited on the road or on the roadsides. Some of it is removed with street cleaning, but the rest accumulates in the soil.
- **Road runoff:** A considerable percentage of tyre wear (around 25-55%) gets carried away with rainwater or snowmelt and ends up in sewers and/or surface water. Some particles may be removed with wastewater treatment, but a large part inevitably remains within the soil and water environments. In London, gully pits aid in reducing this impact by capturing a significant portion of solids and tyre and road wear particles (TRWPs) from stormwater, with retention efficiency varying between 20% and 50% based on rainwater flow velocity [18].

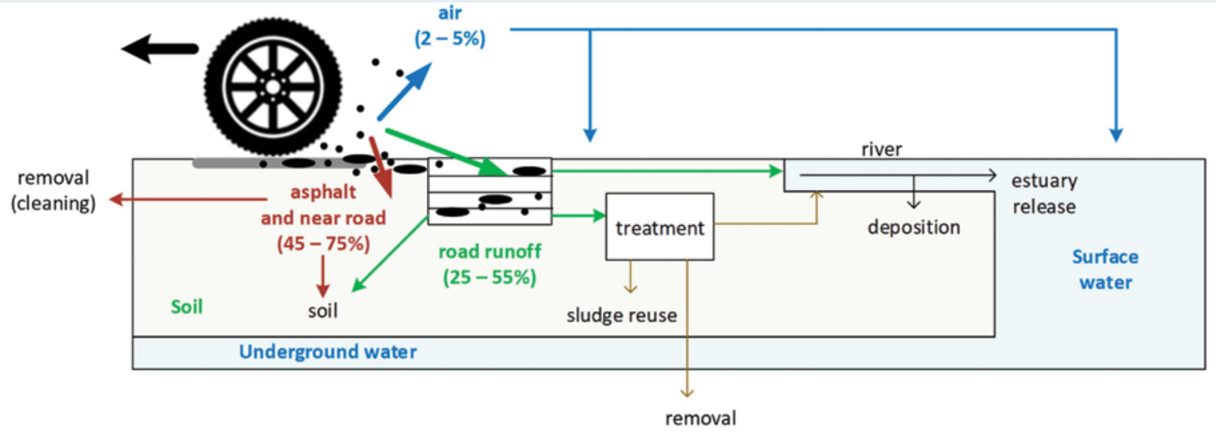


Figure 17: A schematic model of tyre wear sources and environment contamination pathways [3].

Finally environmental factors like humidity and temperature play a significant role in tyre wear, with literature demonstrating that:

Key finding #3.15: Between 0 and 20°C, tyre wear remains consistent. However, when the ambient temperature exceeds 20°C, a significant increase in tyre wear of about 2.7% per degree Celsius is observed [45] [44]. This problem is likely to be exacerbated as global temperatures increase.

Unlike PM from brake wear, there are no results with a harmonised methodology for measuring tyre wear yet, therefore, there is still great uncertainty and variability. The identification of tyre wear particles has primarily been based on laboratory testing (drum method or chassis dynamometer) and on-road measurements (e.g. convoy method). However, there are notable differences between laboratory and on-road measurements. Laboratory testing may not fully replicate the exact stresses experienced at the tyre-road interface, while on-road measurements are influenced by additional factors such as particle resuspension from nearby traffic, weathering, and variations in road surface roughness [46]. Therefore, there are often large discrepancies in the literature varying across a range spanning five orders of magnitude, as has been also revealed by the literature review conducted for this study (see Table 10 in Annex). This is also in agreement with the literature findings of Saladin et al. [47]. Nevertheless, in a literature review of all recent measurements, the authors concluded that:

Key finding #3.16: The mean tyre abrasion rate of passenger cars in the EU was estimated at 96 mg/km/veh [13], while the same value for the UK was reported to be only 67 mg/km/veh, by another study [48]. The average PM10 emission factor is around 3.6 mg/km/veh with 1.6 mg/km/veh of it is PM2.5 while PN10 was found to be 4x1010 /km/veh. More details on particle size distribution and its share over total tyre wear can be seen in [40].

However, the average emission factors at European level used by the European Environment Agency (EEA) emission inventory Guidebook and COPERT rely on old data and are much higher than the recent literature findings: the reported average emission factors equal to 6.4 mg/km/veh for PM_{10} and 4.5 mg/km/veh for $PM_{2.5}$. Similarly, the UK national inventory [32] results to 7.5 mg/km/veh for PM_{10} and 4.1 mg/km/veh for $PM_{2.5}$ utilizing the same methodology adjusted to UK's fleet. Therefore, this study strongly recommends that both European and UK emission inventories need to update their emission factors based on the up-to-date data. This is also recommended by another two studies [47], [49].

3.4 Road wear emissions

Road wear emissions result from the gradual degradation of road surfaces, due to their friction with vehicle tyres during driving, braking, and steering. Tyre and road wear are very closely linked.

Key finding #3.17: It is often challenging to separate the individual contributions from tyre and road wear to airborne particles. Therefore, they are frequently studied together as tyre and road wear particles (TRWPs).

Another challenge in evaluating road wear emissions is the contribution of road dust resuspension to PM emission factors. Road dust resuspension occurs when small particles are lifted by the shear forces generated at the tyre-road interface and get carried away due to the turbulence of passing vehicles, winds etc. These particles originate not only from direct road abrasion, but also from other sources such as brake and tyre wear, soil resuspension and construction activities. Accurately isolating road wear emissions from road dust resuspension is challenging, therefore resuspension is often excluded from studies to avoid double counting. Nevertheless, literature suggests that:

Key finding #3.18: Direct abrasion from road surfaces contributes minimally to particulate matter (PM) emissions, especially when the road is in good condition. Therefore, when keeping roads well maintained, PM emissions from road surface abrasion are lower than those from other non-exhaust sources like brake and tyre wear [50].

Key finding #3.19: Road wear is the least researched category compared to brake wear and tyre wear, leading to significant emission data uncertainty.

The lack of standardised methodology adds further uncertainty regarding the emission factors and the impact of each parameter on road wear emissions.

The average abrasion rate of road surfaces typically ranges from 0.04 to 0.5 mm per year [29], [51], [52], depending on multiple factors. Specifically:

Key finding #3.20: Road wear emissions depend heavily on the road, tyre, and vehicle characteristics, as well as the driving and environmental conditions.

For all the above reasons, the literature review performed in the context of this study, reveals that the average PM_{10} emission factors range from about 3 to 40 mg/km/veh (including resuspension).

The data gathered is shown in Table 11 of the Annex. The values used in the EEA Guidebook and COPERT inventory is 7.5 mg/km/veh and 4.1 mg/km/veh for PM_{10} and $PM_{2.5}$, respectively but they are based on old data. UK national inventory [32] results to 7.5 mg/km/veh for PM_{10} and 4.1 mg/km/veh for $PM_{2.5}$ correspondingly following the same methodology adjusted to UK's fleet.

Box 3: Types of roads

Road surfaces are generally categorised into two types: paved and unpaved. Paved roads are constructed from a base mixture of aggregates of various sizes, such as bitumen or cement, combined with modifiers like fillers and binders. The specific chemical composition of these mixtures is determined by the selection and proportion of their components. Paved road surfaces are broadly classified into concrete or asphalt types:

- Concrete roads, which are made from mineral aggregates, sand, and cement. Detailed information regarding the chemical composition of the concretes used in road construction and the dust emitted from these surfaces remains limited in the literature.
- Asphalt roads, which are the most common globally, and are composed of approximately 90% mineral aggregates, 5% bitumen, and a small percentage of mineral fillers.

Paved roads can also be categorised based on factors such as construction method, deformability, load-bearing capacity, and materials used for the driving layer. E.g., according to their deformability, they are classified into three types: susceptible, semirigid and rigid.

On the other hand, unpaved roads do not have a smooth, hard surface and are usually rough or uneven to drive on. Typically, they are made up from dirt, gravel, or crushed stone, and they are usually uncommon in urban areas like London.

Despite advancements in identifying non-exhaust emission (NEE) sources, knowledge gaps remain due to the complexity of influencing factors. Bridging these gaps is essential to understanding the necessity of mitigating NEEs.

The following chapter examines the chemical composition of the particles from NEEs and their overall impact on air quality and human health, laying the foundation for targeted interventions.

4 Chemical composition of particulate matter and impacts on health, soil & water

In recent years, a growing body of research has highlighted the biological and environmental impacts of non-exhaust emissions (NEEs), revealing their significant toxicity. Particles emitted from brakes, tyres, and road surfaces pose severe health risks, including respiratory and cardiovascular diseases, and contribute to premature deaths. Beyond their implications for human health, these emissions also harm soil and water quality, disrupt ecosystems, and contaminate natural resources. This chapter explores the chemical composition of these particles and their associated health and environmental consequences.

Once released into the environment, brake, tyre, and road wear particles can enter the human body through inhalation, ingestion, or skin absorption. These particles, especially fine particulate matter (PM), penetrate deep into the lungs and bloodstream, causing serious health risks. Exposure to such emissions is linked to respiratory diseases, cardiovascular problems, and DNA damage, which may ultimately lead to premature death [53]. The sources of non-exhaust emissions and their impacts on human health and the environment are summarized in **Box 4**.

Key finding #4.1: Abrasion from brakes, tyres, and road surfaces generates particulate matter that impacts various environmental and biological receptors through two main pathways: human exposure and environmental deposition.

Brake, tyre, and road wear emissions significantly affect human health, targeting multiple biological systems and contributing to various diseases. In cell-based studies, brake wear particles reduce cell viability and cause toxicity, DNA damage, and oxidative stress [54], [55]. These cellular effects are largely attributed to oxidative and inflammatory responses driven by the metal content of brake emissions [54], [55], [56], [57].

Box 4: Non-exhaust emissions and their environmental impact

Particles released from brakes, tyres, and road surfaces spread across multiple environments, posing risks to both nature and human health. The various sources of non-exhaust emissions (NEE) from road transport and their effects can be summarised in Figure 18. Understanding these pathways helps us address the broad impacts of road traffic-related pollution on ecosystems and human health.

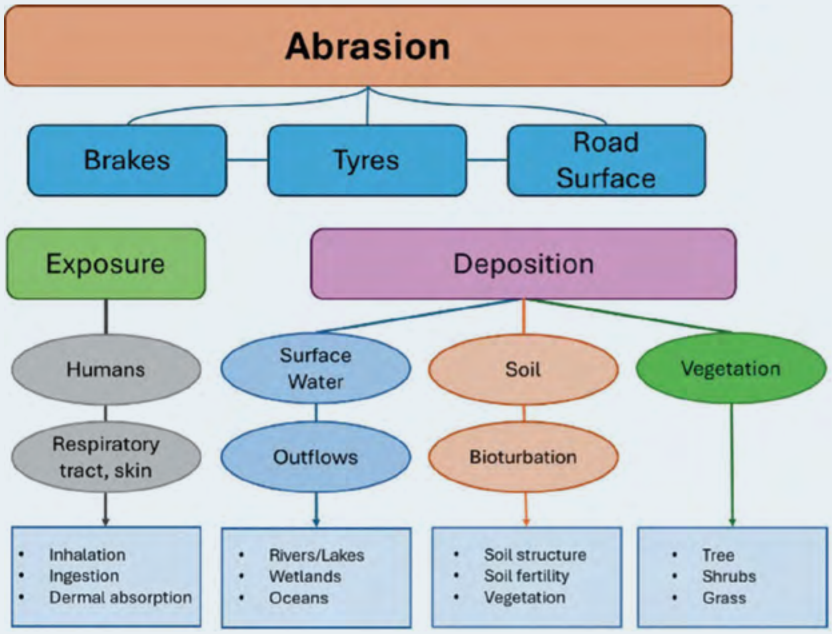


Figure 18: Non-exhaust emission sources and their effects [28].

Particles from non-asbestos organic (NAO) and hybrid brake pads can cause respiratory inflammation, with exposure to $PM_{2.5}$ from NAO and ceramic brake wear leading to a concentration-dependent rise in cytotoxicity. NAO brake pads can also induce oxidative stress as well as increase the expression of genes associated with hypoxia [58], [59]. Tyre wear particles are also linked to respiratory issues, including bronchitis, pneumonia, chronic obstructive pulmonary disease (COPD), and coughing. Specifically, they are associated with $PM_{2.5}$ and PM_{10} exposure, with elements like zinc (Zn) linked to premature mortality. Reproductive health is affected, as $PM_{2.5}$ exposure from brakes and tyres leads to oxidative stress and cell death.

Neurological effects are of particular concern, as $PM_{2.5}$ particles can penetrate the brain via alveolar pathways, contributing to neurological disorders. Cardiovascular impacts are significant as well, with $PM_{2.5}$ and PM_{10} exposure linked to increased stroke risk, blood pressure changes, and heart attacks. Metals within these particulates, including copper (Cu), iron (Fe), zinc (Zn), and sulphur (S), are associated with premature death. Across all body systems, $PM_{2.5}$ has been linked to cancer, underscoring the substantial health risks posed by particulate matter emissions from brake and tyre wear [3], [60], [61]. More detailed information is given in Table 12 in the Annex.

Key finding #4.2: $PM_{2.5}$ presents significant health risks because it can penetrate deeply into the lungs and enter the bloodstream. Exposure to these particles is associated with various negative health outcomes, including respiratory illnesses, cardiovascular issues, and even DNA damage. In the UK, a $PM_{2.5}$ level of 10 µg/cm³ was linked to a 2.12% increase in hospitalizations or heart attack fatalities [60]. At the same time, exposure to $PM_{2.5}$ is estimated to reduce the life expectancy of the population by about 8.6 months on average [62].

Black carbon (BC), also known as soot, is a mix of different carbon compounds. It is a type of light-absorbing material with unique optical and radiative properties that set it apart from other types of aerosols. It is produced from both exhaust emissions due to the incomplete combustion of fossil fuels like gas, diesel, and coal and non-exhaust emissions due to the friction between the brake pad and brake disc (brakes) and the friction between tyre and road (for tyres and roads). Therefore, BC makes up a significant part of particulate matter (PM) [63]. Since BC emission accounts for a large fraction of PM emissions, non-exhaust sources, like brake discs are probable to also contribute to the total BC emission in the air. Black carbon levels are likely proportional to PM_1 (particles with a diameter of 1 micron or less) emissions from disc brakes, with a higher fraction in PM_1 compared to combustion exhaust. Surface scorching of brake pad material appears to reduce black carbon emissions from disc brakes, while a high graphite content in the brake material tends to increase them [64]. However, knowledge about black carbon emissions from non-exhaust sources in road transport, such as brake, tyre, and road wear, remains incomplete.

Black carbon poses a significant global environmental challenge, negatively impacting both human health and the climate. Inhalation of black carbon has been linked to health issues such as respiratory and cardiovascular diseases, cancer, and even birth defects. Additionally, its capacity to absorb light as heat makes it a driver of climate change [63]. It worsens global warming, snow and ice melt, monsoon and weather patterns, flood risk, and heat stress. Black carbon is a dangerous air pollutant that plays a major role in over 8 million premature deaths caused by air pollution each year, as well as in the immense economic burden, amounting to trillions of dollars annually (6% of global GDP [65].

Key areas for future research include the effects of traffic conditions—such as vehicle speed, braking force, temperature, humidity, and precipitation—on BC emissions and the shape and structure of non-exhaust BC particles. Advancing this knowledge could inform legislation aimed at reducing BC emissions, yielding benefits for both public health and global warming mitigation.

Whilst most of the particles emitted from non-exhaust emissions settle in the soil, a significant portion enters aquatic ecosystems, and a smaller fraction becomes airborne [13]. PM is not only harmful to health but also affects crop yields and food production. In aquatic environments, PM impacts the survival and productivity of fish and other organisms [3]. Pollutants in soil and water may also damage cardiovascular health by causing inflammation and disrupting the body's natural cycles.

Particles can be carried over long distances by wind and then settle on ground or water, with effects including acidification of lakes and streams, nutrient depletion in soil, and changes to ecosystem diversity. These pollutants also contribute to acid rain, damaging forests and farm crops, changing the nutrient balance in coastal waters and large river basins [66].

Key finding #4.3: PM pollution affects soil and water quality by contaminating precipitation, leading to changes in soil chemistry and acidification. This, in turn, harms plants, crops, water and disrupts ecosystems, impacting overall environmental health.

Particles from tyre, brake and road wear further amplifies environmental and health risks. These contaminants can enter the human body through the nose, mouth, or skin, causing acute and chronic health issues. Short-term effects include headaches, coughing, chest pain, nausea, and skin irritation. People working with contaminated soil or living nearby face elevated risks, as inhaling airborne dust can result in multiple health problems [13], [60], [3].

Heavy metals in coarse particles (PM_{10}) often settle on soil or surface water, with zinc (Zn) being the most prevalent. Studies of leaching from tyre wear particles in water have identified a wide range of substances, including heavy metals like copper (Cu), cadmium (Cd), chromium (Cr), and lead (Pb), along with organic compounds such as polycyclic aromatic hydrocarbons and benzothiazoles.

The composition of brake and tyre wear emissions largely depends on the materials used in brake pads and discs, tyres, and roads. Brake emissions comprise mostly coarse particles (PM_{10}) from friction, with fine particles ($PM_{2.5}$) from heat-related processes. Commercial lining materials vary widely, but iron (Fe), copper (Cu), zinc (Zn), barium (Ba), and lead (Pb) are the most abundant metals in brake linings, along with compounds from organic material breakdown [67], [68], [69]. Differences in the chemical composition of brake wear emissions are observed between heavy-duty vehicles (HDVs) and light-duty vehicles (LDVs). For HDVs, copper (Cu) dominates, followed by barium (Ba) and iron (Fe), while for LDVs, barium (Ba) dominates, followed by iron (Fe) and zinc (Zn). Further details are provided in Table 13 of the Annex. Data is based on preliminary measurement results from ongoing research.

Recent studies suggest that non-asbestos organic (NAO) brake pads contain 4–6 times more copper (Cu) than low-steel, which may account for their differences in toxicity. Copper is a harmful substance that poses risks to both biological systems and aquatic environments. However, copper is not the only elemental component of brake wear that induces acute inflammatory responses. Other metals, such as iron (Fe), nickel (Ni), vanadium (V), and zinc (Zn), have also been identified as contributing to the toxicity of PM sources. The toxicological differences between the two brake wear groups could not be explained by the iron content in the brake pads of both groups, but may be due to copper or other components, like titanium (Ti), barium (Ba) or zirconium (Zr) which are more prevalent in NAO-based brake pads.

Variations in the toxic potency of brake wear particles may be linked to their chemical composition, with low or zero-copper pads being the least harmful for pulmonary inflammation after inhalation. Since particle hazards depend on composition, targeted measures are needed, and brake wear particles should be considered in air pollution control strategies [70], [58].

Tyre wear also releases particles, including larger fragments that contain carbon (C 77%) and metals like iron (Fe), calcium (Ca), and zinc (Zn, ~1%) as well as fine particles with aluminium (Al) and silicon (Si). Sulphur (S) is often found in fine particles ($PM_{2.5}$), particularly from tyres tested under high-friction conditions. Metal content in tyre wear can vary. Zinc (Zn) levels, for example, differ slightly depending on the vehicle type, with higher levels in HDVs emissions than in passenger cars [71], [72], [73]. The toxic compound 6-PPD-quinone, a byproduct of tyre preservative oxidation, is particularly concerning, as it has been shown to kill coho salmon and trout and can be absorbed through plant roots. Additional details on the composition of tyre wear emissions are presented in Table 14 and Table 15 of the Annex.

Key finding #4.4: Brake wear emissions are primarily metal based, with up to 60% iron. In contrast, tyre wear particles consist of 53% minerals. Both brakes and tyres are sources of black carbon [52], [64], [68].

Particles from road surfaces are influenced by pavement materials, which vary based on expected traffic loads and climate. Statistical data on road wear is summarized in Table 16 of the Annex.

The extensive impact of particulate matter from brakes, tyres, and road wear underscores the urgent need for targeted regulations and effective mitigation strategies. Addressing the health and environmental risks posed by these emissions requires a multifaceted approach to minimize their release and long-term effects. In addition to regulatory measures, innovation plays a pivotal role in combating non-exhaust emissions. The next chapter focuses on existing policies and explores potential measures and innovations to control emissions, paving the way for a more sustainable and health-conscious approach to managing these pollutants.

5 Policy and technical interventions for tackling non-exhaust emissions

In the pursuit of cleaner urban air and compliance with stringent World Health Organization's (WHO) guidelines on particulate matter (PM), addressing non-exhaust emissions (NEEs) has become both a regulatory and environmental imperative. This chapter explores a diverse array of strategies aimed at reducing non-exhaust emissions, categorising them into preventive and mitigating measures. From influencing travel behaviour and embracing technical innovations to capturing dispersed particles, these interventions collectively represent a state-of-the-art portfolio of actions. They support meeting the emerging non-exhaust emission limits introduced under the Euro 7 regulation, setting the stage for more comprehensive urban air quality management.

5.1 Regulatory framework

Addressing emissions from brake and tyre wear has become a critical focus for international policymakers. The World Forum for Harmonization of Vehicle Regulations (WP.29), under the guidance of the United Nations Economic Commission for Europe (UNECE) [74], has been spearheading initiatives to establish standard methodologies.

Figure 19 shows the milestones related to non-exhaust emissions from road transport under the United Nations global technical regulation. In response to the need for accurate, harmonized measurements, the Particle Measurement Programme (PMP) of the United Nations Economic Commission for Europe (UNECE) Working Party on Pollution and Energy (GRPE), has developed a Global Technical Regulation (GTR 24) [75], providing standard protocols for measuring brake wear particles from light-duty vehicles (LDVs). Within the regulation, parameters such as test cycle (Worldwide Harmonized Light Vehicles Test Procedure, WLTP-B), facility requirements and test conditions are defined. An amendment in January 2024 introduced vehicle-specific friction share coefficients for electrified vehicles, which are defined as the reduction percentage of the brake emission factors for hybrid, plug-in hybrid, and battery-electric vehicles compared to the equivalent conventional vehicles. However, no equivalent method currently exists for heavy-duty vehicles; a standardized method by the PMP is expected around September 2025.

Efforts to regulate tyre wear began in 2022, with a task force developing two measurement methodologies for tyre abrasion: an on-road (convoy) method and a laboratory (drum) method [76]. Tyre types have been classified into C1 (passenger cars), C2 (light commercial vehicles), and C3 (heavy-duty vehicles), with proposed limits expected to apply in the coming years after conducting a market assessment and defining the reference tyre for each class. A testing campaign is underway aiming to evaluate the market situation of tyre abrasion rates.

Key finding #5.1: The increasing contribution of non-exhaust particulate matter to air pollution is driving efforts to harmonize brake and tyre emissions testing and performance requirements globally. Based on the work of WP.29 of the UNECE, the Euro 7 regulation of the EU [77] sets emissions limits from brake wear and tyre wear, marking the first regulatory action globally on non-exhaust emissions from road transport.

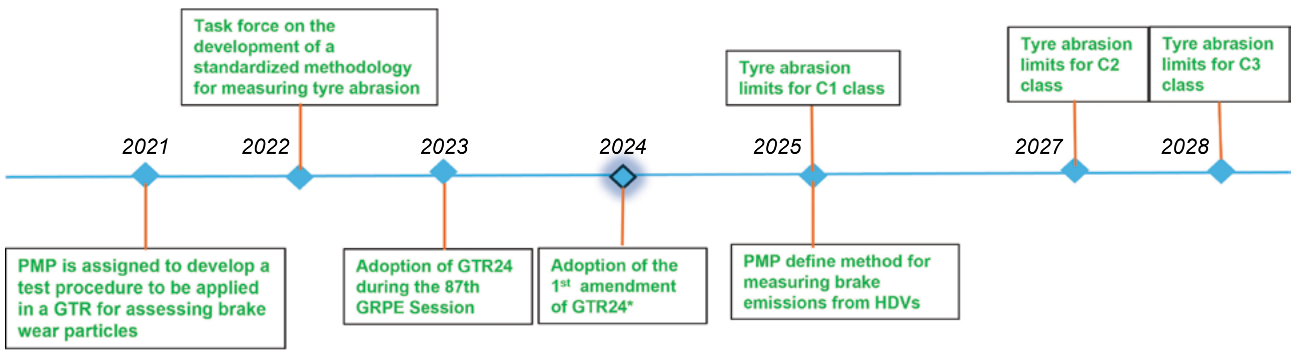


Figure 19: Milestones related to NEEs from road transport at UN GTR.

To date, only limits for PM_{10} from brake wear have been established for light-duty vehicles in the Euro 7 regulation (see Table 17 in Annex), for which a harmonized methodology at the United Nations Economic Commission for Europe (UNECE) level exists. The PM_{10} brake emission limits will take effect on new vehicle types from November 2026 and for all new vehicles from November 2027 and onwards. These initial limits range between 3 and 11 mg/km depending on the type of vehicle and fuel type.

To highlight the comparison with exhaust emissions, the equivalent PM limit for tailpipe emissions from light duty vehicles has been 4.5 mg/km since Euro 5. Limits are expected to tighten further after 2030, aiming for 3 mg/km for all new light-duty vehicles by 2035, aligning with the transition to zero tailpipe emission vehicles [78]. No brake emission limits have yet been set for heavy-duty vehicles due to the lack of an equivalent methodology to Global Technical Regulation (GTR24), though limits are expected to apply from 2030 onwards. The exact timeline can be seen in Table 17 of Annex.

Limits are yet to be defined for tyre wear, but the Euro 7 regulation indicates that future limits will be based on the two testing methodologies, one on road (convoy) and one laboratory method (drum), developed under UN WP.29. The Euro 7 regulation already specifies the timeline for tyre wear limits starting with the tyres of passenger cars gradually from July 2028 followed by light commercial (gradually from 2030), and heavy-duty vehicles' tyres (gradually from 2032).

Key finding #5.2: The non-exhaust emission limits of the Euro 7 regulation apply across all vehicle types, fuel, and technologies. This regulation is expected to reduce PM from brake wear of new light-duty vehicles (LDVs) entering the market after November 2026 by more than 60% on average compared to the existing equivalent vehicles. However, since Euro 7 brake emission limits apply only to new vehicles, this reduction is expected to be gradually achieved around 20-25 years later when all existing vehicles will be phased out, if no further measures are taken.

Other existing EU Directives, regulations, and standards that are relevant to non-exhaust emissions are illustrated schematically in Figure 20. Their correlation to non-exhaust emissions from road transport is also described, even though all of them were targeting other limitations and their impact on non-exhaust was only indirect. More specifically:

- In 1998, the European Directive 98/12/EC [79] mandated asbestos-free brake pads, impacting brake wear particle composition and toxicity.
- End-of-life Directive 2000/53/EC [80] restricts hazardous materials such as lead and mercury.
- The Directive 2004/107/EC [81] sets limits on heavy metal concentrations in the air.
- The REACH regulation 1907/2006 [81] governs the safe use of chemicals, indirectly affecting brake and tyre materials.
- The Ambient Air Quality (AAQ) Directive 2008/50/EC [82] sets PM concentration limits.
- The National Emission Reduction Commitments Directive (EU) 2016/2284 [83], sets targets for PM reduction, covering tyre and brake wear, while EU 2020/740 on tyre labelling introduces the possibility of future inclusion of tyre abrasion information.
- The revised Air Quality standards [7] reduces annual concentration limits to 10 µg/m³ for $PM_{2.5}$ and 20 µg/m³ for PM_{10} for 2030, aligning closely with the WHO guidelines.
- The target of the European Union (EU) Zero Pollution Action Plan [84] is to reduce microplastics released into the environment by 30% by 2030 compared to 2016 levels.

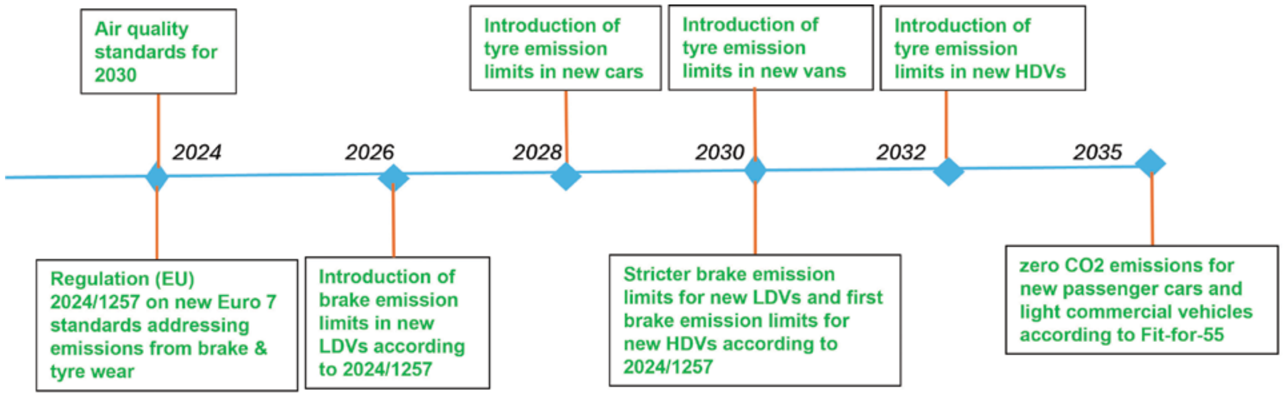


Figure 20: European regulations and standards relevant to NEEs from road transport.

The European Commission recommends Member States use appropriate incentives for older cars to be retrofitted to meet Euro 7 requirements for tyre and brake emissions but without suggesting the technology needed to achieve this [77].

To the authors' knowledge, no direct regulations or standards targeting the mitigation of non-exhaust emissions (NEEs) from road transport have been implemented at the national level to date. The sole exception is Sweden, which has implemented measures such as reducing the period during which studded tyres can be used or banning them in certain areas, alongside other initiatives to improve air quality [85]. Indirect measures, including fleet electrification and city-level interventions like Low Emission Zones (LEZs), modal shifts, and traffic management, have been adopted in various countries. However, these measures primarily address general air quality improvement and do not specifically target NEEs from road transport.

In the UK, the Euro 7 standards have not yet been adopted, meaning no emission limits for brake and tyre wear are currently in place.

Nonetheless, tackling road transport emissions is still a key priority in cities like London, where it is the largest single source of particulate matter among all sectors, contributing to approximately 30% of total PM2.5 emissions. The "Healthy Streets" [86] approach sits within the Mayor's Transport Strategy (MTS) and aims to transform the transport system to prioritise human health and well-being by designing the streets that encourage active travel and use of public transport (e.g. provision of pedestrian and cycling infrastructure, good shade/shelter, rest points etc). Another key initiative is the Ultra-Low Emission Zone (ULEZ) and Low Emission Zone (LEZ), which promote specifically adherence to Euro 4 standards for petrol and Euro 6 for diesel, thereby reducing exhaust emissions from various vehicle types (more details on Table 18 in the Annex). However, these schemes do not directly address NEEs. The UK Government should take a leading role in collaborating with industry and other stakeholders to identify and implement solutions for reducing emissions from tyre and brake wear, alongside measures outlined in the Clean Air Strategy [87].

5.2 Bilateral consultations and workshop with experts

An important part of our research, following setting the scene on the non-exhaust PM pollution sources and existing regulatory framework, was the identification of effective prevention and mitigation measures against NEE pollution from road transport. The process started with a comprehensive market screening, which included a thorough literature review of studies, technical reports, similar project results, and the most recent advancements on the subject. This initial screening resulted in a broad list of possible measures against NEEs ranging from purely technological solutions to traffic and air pollution management and policy strategies with the potential to reduce PM emissions from brake, tyre, and road wear. To refine this list and further investigate the potential measures in greater detail, bilateral discussions were performed with industry experts, mostly original equipment manufacturers (OEMs) and representatives from automotive and engineering companies. Virtual bilateral meetings were carried out from September through November 2024 with a total of 9 companies, including Endurance Overseas, The Tyre Collective, Michelin, and IAV. These discussions resulted in the identification of opportunities and constraints for each measure and the establishment of a more focused selection of the most promising interventions, which were both technically viable and in alignment with industry priorities and the Euro 7 regulation.

Our findings from the literature review and the bilateral meetings were used as input to the next stage of the research, which was carrying out a dedicated workshop to further discuss and evaluate the selected interventions in terms of timescales, technical and economic feasibility, and ease of implementation, as well as ultimately identify the most effective interventions to be modelled and assessed through a cost-benefit analysis (CBA). At this stage, the potential interventions were divided into three groups: reducing NEEs at source by changing travel behaviour, reducing NEEs at source through technical interventions, and reducing NEEs once emitted. A total of 39 key stakeholders attended the workshop, which took place virtually on 19 November 2024, including policymakers, consultants, and fleet operators, representing London and other UK and European cities comparable to London, like Stockholm, Barcelona and Milan. The outcomes of the bilateral and workshop consultations are outlined in Section 5.3.

5.3 Potential measures against non-exhaust emissions

Measures against non-exhaust emissions (NEEs) can be categorised into two main types: preventive measures, which aim to stop or reduce the generation of particulate matter (PM) at the source, and mitigating measures, which focus on capturing or minimising PM already dispersed into the atmosphere. Preventive interventions can be further divided into policy and management measures targeting changes in travel behaviour and technical measures to enhance vehicle emission efficiency, such as wear-resistant components and materials.

We note that, in the latter case, the efficiency and cost of each technical solution discussed for the most part refers to light-duty vehicles (LDVs), since the data for heavy-duty vehicles (HDVs) is still limited and characterised by higher uncertainty.

In the following paragraphs, a number of potential interventions are discussed in detail with regards to their effectiveness against NEEs. The discussion is based on thorough market screening, e:misia's on-going research projects, bilateral consultations with industry experts, and finally a workshop with policymakers (see also Section 5.2). A summary of all the interventions is given in Table 19 of the Annex, along with an evaluation in terms of efficiency, ease and cost (where available) of implementation, opportunities, barriers and the key stakeholders necessary to make them a success.

A. Reducing NEEs at source by changing travel behaviour

A1. Expansion of Low Emission Zones (LEZs)

LEZs are designated areas within an urban environment, where only vehicles meeting specific emissions standards are allowed to enter, or are allowed to enter if paying a fee. In 2022 there were a total of 320 declared active LEZs in Europe (in cities including London, Stockholm, Milan, Barcelona, Berlin etc.), projected to rise to as many as 507 by the end of 2025 [88], while in the UK there are currently 17 active LEZs [89]. Although none of them are targeting NEEs directly, they have proven to be very effective against exhaust emissions; the Ultra-Low Emission Zone (ULEZ) has had an impact on improving air quality across the capital [90].

In 2024, compared to a scenario without the ULEZ, harmful roadside NO_2 concentrations are estimated to be 27% lower across the whole of London; and $PM_{2.5}$ exhaust emissions are estimated to be 36% across London in 2024 due to all phases of the ULEZ. German cities on the other hand, have reported annual reductions of approximately 7% in PM_{10} concentrations and 4% in NO_2 concentrations solely from LEZ implementation [91].

The introduction of the Euro 7 regulation, which for the first time sets limits for brake wear emissions, is a great opportunity to expand LEZs to consider brake, tyre, and road wear as an important source of pollution, and potentially mitigate particulate matter emissions. According to consultation with experts, this intervention is expected to have benefits against NEEs, through encouraging alternative transportation modes and reducing kilometre driven by high-emission vehicles. However, it is also anticipated to face considerable socio-economic challenges at not only the local but also the national government level, as some countries, like the UK, Spain and France, have developed national clean air frameworks that make the implementation of LEZs in major cities mandatory [88]. Enforcing and ensuring compliance with additional LEZ rules may be challenging for authorities due to political, legal and/or public opposition. LEZs ban non-compliant vehicles from entering the designated areas if local powers have the authority to enforce the ban, or a charge-based scheme is employed if they do not.

In conclusion, the expansion of Low Emission Zones (LEZs) to include NEEs could be one effective, short-term intervention against NEEs. However, implementation might prove to be moderately difficult and would not be relevant to all cities, especially when there are not clear national legal and financial frameworks to support public acceptance and implementation. To this end, raising awareness through e.g., dedicated campaigns regarding NEEs and the potential benefits of LEZs against them, is essential for their acceptance by vehicle owners and the public in general.

A2. Mode shift to other means of transport

Is a possible initiative against non-exhaust emissions, with an excellent potential to directly reduce kilometres driven and consequently reduce PM emissions [92]. Reducing the number of vehicle kilometres driven is the best way to reduce road transport emissions, as it eliminates emissions at source. An example of this is the target set in the London Mayor's Transport Strategy for 80% of journeys to be made by walking, cycling, or public transport by 2041 [93]. According to consultation with experts, other cities across Europe have also already made extensive efforts to encourage walking, cycling and public transport and discourage the use of private vehicles e.g. through improvements in active travel infrastructure and the provision of public transport, facilitating access to cycles, amending public transport fares, introducing access control restrictions for private vehicles etc.

Feedback from the workshop suggested that, while mode shift requires significant funding and cooperation among many stakeholders (local government, transport authorities, vehicle owners and the public in general), thus making their implementation challenging, they are anticipated to be effective in reducing not only exhaust emissions but also NEEs and should be prioritised in the short to medium terms. Moreover, improving the attractiveness, convenience, and efficiency of public and active transportation modes, along with communicating their environmental and health benefits, is expected to be a more effective approach than the implementation of punitive measures.

A3. Traffic flow and volume control

Includes solutions to manage and improve traffic, which can be very helpful in tackling NEEs, especially in cities' major urban roads, where the traffic is generally heavier, i.e. there are more vehicles circulating (more traffic volume), often creating congested conditions (disrupted flow). According to LAEI, a network of London's major roads known as "red routes" constitute just 5% of the city's road network, but carry up to 30% of its traffic [8]. Heavy traffic generally creates more NEEs due to more frequent and stronger acceleration/deceleration events which lead to increased brake and tyre wear **(see also key findings #3.3 and #3.11)**, and also due to increased road wear and particle resuspension from the higher number of vehicles circulating. Another important aspect of traffic is that congestion is directly linked with driver and passenger extended exposure to PM emissions.

For example, the average speed in London during peak hours is about 20 km/h, leading to an estimated annual loss of 148 hours per driver in traffic [94]. Therefore, controlling traffic flow and reducing volume is very important to minimise the associated health implications.

Traffic management solutions typically involve local interventions, such as traffic signal timings, road, junction, and roundabout design and re-configuration, as well as highway access control restrictions (e.g., low traffic neighbourhoods in London, local road closures/banned turns, highway space reallocation), and parking restrictions. Moreover, technological innovations such as traffic management tools which integrates emissions calculations into a traffic simulation software can be very helpful in modelling traffic control measures and getting immediate results on their effectiveness [95]. An example of an effective congestion charging scheme is the case of Stockholm, where the congestion charge resulted in a 30% decrease in traffic volume. Additionally, a drop of about 14-20% in PM_{10} emissions was reported, partly due to a decrease in NEEs [96]. According to consultations with experts, other opportunities for national and/or local authorities to implement the measures above include, but are not limited to, financial initiatives (e.g. taxation on fuel, kilometres driven etc.), as well as efforts to raise public awareness against the overuse of private vehicles. Potential barriers making the implementation of the above challenging, include political and/or public opposition primarily on taxation and fines, while there are some concerns regarding whether creating space for smoother driving ends up promoting the use of private vehicles.

Therefore, adding NEE considerations to current traffic management policies has the potential to make a considerable impact against them in the short term, but it should be treated primarily as a complementary intervention, targeting the private vehicles that will continue to circulate in urban environments, even with the successful implementation of measures like mode shift.

A4. Reducing vehicle speeds

Includes a number of policies targeting to change the pattern of vehicle mobility and driving style/behaviour. One popular, cost-effective way of achieving this is the reduction of mandated speed limits, which in some cases has been proven to be very effective against exhaust emissions like NOx, CO_2, and particulate matter from road transport [97]. In the city of Madrid, for example, reducing the speed limit from 50 to 30 km/h led to a reduction of about 25-30% in PM emissions [98]. Although, to the best of the authors' knowledge, there are no publications linking speed reductions to lower levels of PM_{10} and/or $PM_{2.5}$ pollution from non-exhaust sources specifically, the OECD have reported that higher vehicle speeds generally cause more tyre and road wear, as well as increased levels of road dust resuspension. Additionally, aggressive driving styles, which are a common result of higher speeds within urban environments, such as stronger acceleration/deceleration events and frequent braking, are associated with increased brake wear. It is therefore necessary to ensure smooth driving behaviour alongside reducing speed limits [96], [97].

Local governments can implement lower speeds either through the introduction of limits and imposition of fines or by encouraging voluntary slower and smoother driving styles [99]. However, effective enforcement can be challenging, and public resistance may arise. In this context, the adoption of additional measures, such as speed cameras, speed bumps, roundabouts, lane narrowing, speed/acceleration limiters (see also B4), and in-vehicle driver assistance systems (DAS), like the intelligent speed assistance (ISA) system can also play a crucial role in addressing speeding in the short term [96], [97]. Public awareness campaigns emphasising the environmental, health, and safety benefits of lower speed limits can improve acceptance.

A5. Acceleration of fleet electrification

Is a measure also being examined as to whether it has the potential to reduce NEEs. Brake wear emissions are positively affected by electrification as regenerative braking, a feature of hybrid and electric vehicles, can reduce brake wear emissions by 10-48% for HEVs, 66% for PHEVs, and 83% for BEVs (see also key finding #3.8). On the other hand, perhaps the most important downside to electric vehicles (EVs) is their increased weight, which has a negative effect on particulate matter emissions from tyres. From our literature review it was concluded that an EV with a 20% higher mass than a corresponding internal combustion engine (ICE) demonstrated a 20% increase in tyre wear (see also key finding #3.13). A similar increase is also assumed for road wear, even though the uncertainty is higher.

The dual impact of electric vehicles was also confirmed by original equipment manufacturers (OEMs) during the workshop, raising the issue of whether the margin is positive in respect of EVs' overall non-exhaust emissions. The results of a 2025 study revealed that the overall effect of electrification depends strongly on driving conditions and is positive in the case of city driving, where regenerative braking is used more frequently, but negative in the case of freeway driving, where the increased mass of the vehicle plays the most important role. The study concluded that, battery-electric vehicles (BEVs) produce less NEEs as long as a minimum of 15% of its travelling is in-city driving [100].

Based on the above, faster fleet electrification seems like a promising long-term intervention against NEEs for policymakers to advocate for, while simultaneously giving consideration to vehicle lightweighting measures, like implementing vehicle weight taxation schemes, using low-density materials or limiting battery range and/or capacity to counterbalance potential trade-offs [99]. At the same time, it is important to consider that fleet electrification eliminates exhaust emissions and improves air quality by removing pollutants like nitrogen oxides (NO_x) and particulate matter (PM), which are harmful to health, especially in cities. Moreover, electric vehicles produce zero tailpipe CO_2 emissions, thus significantly reducing their direct contribution to climate change. These effects combined with the NEE benefits in urban areas make faster fleet electrification something that should be encouraged by countries/cities.

Vehicle design and manufacturing can be a very long process, while the impact of new materials will only become apparent in the long term. This is especially true since some materials necessary to make electric vehicles lighter may not yet exist or be fully developed. The same applies to reduced battery weight, which is also important for vehicle lightweighting. Additionally, it is essential that more research and development activities are carried out to better understand the correlation of EVs to increased tyre wear and find ways to improve this trade off [99]. Finally, according to consultation with experts, a possible challenge to the successful implementation of faster fleet electrification is that national and/or local authorities might face political and public opposition due to the financial strains that the necessary infrastructure rollouts and vehicle upgrading will inevitably bring. An opportunity to tackle the economic barriers, would be to secure private investment and/or public grants, although the latter will not always necessarily be focused on non-exhaust emissions (NEEs) specifically.

A6. Driving style/behaviour

Is one of the most important influences on brake, tyre, and road wear, according to feedback from original equipment manufacturers (OEMs), since it affects both the overall amount of PM, and its size, too. Sporty driving for example, which is characterised by high speeds, harsh acceleration/deceleration events and fast cornering, is responsible for the emission of higher amounts of overall PM_{10} due to higher wear rates, compared to slower, smoother driving. One way of reducing emissions through improving driving behaviour is the application of telematics (“black box”) systems that monitor and analyse driving styles. According to recent research findings presented during the workshop, these can be very effective against PM emissions, with the capability to reduce e.g., brake wear by approximately 10%. Telematics systems are used by some insurance companies in order to offer more reasonably priced policies, typically for less experienced drivers, thus creating an opportunity for the insurance industry to contribute to the effective reduction of NEEs.

However, according to the consultations with the experts there are some barriers to successfully changing driving behaviour, such as the limited public awareness of the issue, and political challenges, the most important being the potential conflict with personal autonomy, as individuals may resist such interventions. On the positive side, regulations such as the noise level reduction control service in Barcelona can create an indirect framework for influencing driving style. Traffic is the primary source of noise pollution in Barcelona [101], therefore some of the measures included in the plan against noise pollution for 2022-2030 are focused on traffic calming, which is also beneficial against NEEs. These measures include implementing the “Urban Mobility Plan (PMU) 2024” which targets for 81.5% of the city’s journeys to be made by public and/or active transport, the reduction of vehicle speeds from 50 km/hr to 30 km/hr, as well as the establishment of superblocks [102]. These have already been discussed as to their effectiveness against NEEs in the previous sections (see measures A2 for modes shift, A4 for speed reduction, and section 2.2 for superblocks).

In addition to implementing those measures, consultations with experts concluded that it is very important to educate the public on the benefits of smoother driving and encourage voluntary responsible driving habits through public awareness initiatives. These might include information campaigns or driving courses for environmentally friendly and economic driving aimed at specific groups e.g. company employees.

Key finding #5.3: NEEs can be reduced through interventions that influence the composition of the vehicle fleet operating in a city, the volume of kilometres travelled, the flow of vehicles and vehicle driving styles.

B. Reducing NEEs at source through technical interventions

B1. Wear-resistant braking components and materials

Play a crucial role in reducing particulate matter (PM) emissions from road transport. In London, the majority of PM_{10} emissions from traffic are attributed to brake wear. In the case of passenger cars, among the various braking systems, drum brakes generate approximately 23% less wear compared to disc brakes (key finding #3.4). Moreover, replacing traditional grey cast iron (GCI) discs with carbon composite (CC) discs can reduce PM_{10} emissions by 81%, $PM_{2.5}$ by 74%, and particle number (PN) by 61% on average.

Similarly, applying hard-metal coatings (HMCs) on GCI discs reduces PM_{10} by 57%, $PM_{2.5}$ by 60%, and PN by 57% (key finding #3.5). Additionally, replacing low-steel (LS) pads with non-asbestos organic (NAO) pads can cut PM_{10} emissions by 62%, $PM_{2.5}$ by 55%, and PN by 64% (key finding #3.6), although preliminary data from chemical and toxicological analysis show that the higher copper content in NAO pads compared to low-steel brake pads can be toxic to human health [58].

According to the bilateral discussions with original equipment manufacturers (OEMs), most of the components discussed above have already been developed and are characterised by high technology readiness levels (TRLs). However, the Euro 7 regulation creates not only opportunities but also challenges for their widespread adoption, due to higher costs of low-emitting braking components and materials compared to existing counterparts.

Optimised (wear-resistant) brake discs can cost 100 EUR more compared to grey cast iron (GCI) counterparts. Over a standard vehicle lifespan (about 200,000 – 240,000 km), GCI discs typically require about two to three replacements). This is different for battery-electric vehicles (BEVs), where regenerative braking reduces reliance on mechanical brakes, leading to less disc wear and therefore less disc replacements, if any. There is some evidence that optimised discs may need less replacements than GCI, so the higher cost may be offset by the need of less replacements over the vehicle lifetime [103], [104].

On the other hand, optimised braking pads for passenger cars, i.e., non-asbestos organic pads cost about 15 Euros more than existing low-steel (LS) braking pads, per vehicle, and are expected to require about six replacements (similar replacements to LS pads [105]) in the case of conventional vehicles and around two to four replacements for BEVs over the vehicle's lifetime [24]. There are also other options available, e.g., ceramic pads which present other drawbacks, like increased costs (see also Chapter 3).

According to consultation with experts, policymakers can play an important role in easing the challenges, by lobbying for a gradual integration of these technologies. This will help avoid disrupting supply chains, keep the costs lower for consumers, and control the aftermarket in the long term. Moreover, advocating for investments in research and development and adopting harmonised testing methodologies will help to ensure compliance to the new, Euro 7 standards, while launching public awareness campaigns on the benefits of new components and materials will support acceptance by vehicle owners, and the public in general.

B2. Wear-resistant tyres

A 2024 study to estimate the future benefits of the Euro 7 regulation examined three different scenarios of tyre wear emissions reduction compared to today's levels: 10% (basic scenario), 20% and 30% [40]. Although the findings have some uncertainty due to lack of accurate and up-to-date emission factors, especially for heavy-duty vehicles, the introduction of tyre wear limits would have a significant positive impact under all scenarios examined.

The study concluded that a 10% reduction in tyre wear can be achieved by improving or banning high-emitting tyres without altering most existing tyres. This means that with the new limits in place, high-emitting tyres will need to be upgraded (e.g. through changes in their formulation) or removed from the market. In the last case, it is expected that original equipment manufacturers (OEMs) will be able to substitute them with tyres they already manufacture, with an added cost of about 2% per tyre [40]. Achieving reductions of 20-30% would require greater investment and innovation. Tyre wear varies by vehicle type, with electric vehicles (EVs) emitting on average 20% more tyre wear per vehicle over lifetime compared to their internal combustion engine (ICE) equivalent, due to their weight. More accurate estimates will depend on market assessments and the limits of the Euro 7 regulation [40], [106], [107], [108], [109].

For the time being, there are no limits for tyre wear by any regulation, and, according to feedback from the experts, new formulations and tyres are still under development and are characterised by low technology and market readiness levels (TRL and MRL). However, our analysis concludes that wear-resistant tyres have the potential to reduce NEEs, therefore policymakers can impact their future smoother integration in the long term, by incentivising research and development activities for the manufacturers, lobbying for the establishment of tyre wear limits and the development of harmonised testing methodologies to ensure compliance, as well as promote public awareness regarding the environmental and cost benefits of improved tyres, focusing on financial incentives (wear-resistant tyres will by definition need less replacements).

B3. Wear-resistant road materials

Are a potential intervention against NEEs, with efficiencies of about 30-52% in road wear reduction [110]. However, their effectiveness against all NEEs from road transport is often questioned since the literature review has concluded that direct abrasion from road surfaces contributes minimally to PM emissions compared to brake and tyre wear, especially when the road is in good condition (key finding #3.18). Therefore, maintenance condition is just as important an influence factor, if not more important, than the composition and grain size of the materials used, as well as the properties of the road itself (e.g. porosity).

It is often recommended that abrasion-resistant materials are used for road surfaces to reduce road wear. Quartzite, for example, could be considered as an alternative to granite. However, lower road wear does not necessarily lead to reduced PM emissions, as the use of resistant materials, which typically show higher abrasiveness, might even increase tyre wear for example, offsetting any potential benefits. Moreover, the technical requirements of constructing a surface that reduces road and/or tyre wear may often conflict with safety standards. For instance, optimising the road's surface roughness to minimise the wear, may compromise grip, particularly in wet conditions where surface roughness is essential for improved traction [13], [99].

Therefore, it is concluded that local government strategies to decrease emissions through road management should be mostly focused on the short-term effects of routine maintenance and improvement of existing road surface conditions, rather than more difficult and costly solutions like e.g. replacing surface materials of existing roads.

B4. Speed/acceleration limiters

Are technological solutions implemented in vehicles to lower their maximum speed or acceleration capability, while deceleration should not be limited, for safety reasons. They can be very helpful to the implementation of reduced speed limits and the promotion of smoother driving behaviours (especially in terms of ensuring compliance), which both offer considerable benefits against NEEs, thoroughly discussed in A4. Limiters can prove particularly effective for some specific vehicle types where acceleration capacity and speed are not crucial. For example, intelligent speed assistance (ISA) is already being implemented in over a third of London's bus fleets, with the goals to have the majority retrofitted by 2030 [111]. This shows the viability of this technology in the case of fleets like buses or goods vehicles, where reducing speed and acceleration is not only beneficial against NEEs but also improves safety and operational performance.

On the downside, the main barrier identified is that some vehicle manufacturers, particularly those producing high-end models, typically emphasise acceleration as a key selling point. As a result, they are unlikely to limit this function intentionally. In the case of electric vehicles, while maximum speed is often limited to prioritise longer driving range, top acceleration remains a crucial performance factor.

Therefore, even though the reduction of maximum speed might be more acceptable to manufacturers, the focus on acceleration capability will become even more significant for enhancing the prestige of their vehicles [99]. In conclusion, speed/acceleration limiters can be an effective complementary measure if a regulation is set at an international level to aid the more general goals of speed reduction and smooth driving behaviour.

Key finding #5.4: It is possible to significantly reduce NEEs through the introduction of wear resistant brake, tyre and road materials and introduction of speed/acceleration limiting technology, some of which will happen due to Euro 7, but that there are challenges to widespread adoption (cost, market readiness etc) and potential unintended health consequences.

C. Mitigating NEEs once emitted

In addition to minimizing particulate matter formation, there are technological solutions and road cleaning measures available to trap particles as soon as they are generated.

C1. Particle collection/filtration devices for brake/tyre wear

Can be either active (filtration is achieved through a powered system) or passive (filtration relies on natural forces and does not require additional power). Generally, the research on brake filters is more evolved compared to tyre-wear particle filtration, with a few industry solutions tested in both laboratory and real-world settings, claiming efficiencies of as high as 85% [112]. The most recent on-going research that included both on-road and laboratory measurements showed that the average efficiency of brake filters in existing vehicles is about 79% for PM_{10}, and 72% for $PM_{2.5}$. It is important to note that the results of lab measurements may not always coincide with the real-world impact. On the other hand, tyre wear collection devices are also under development, with preliminary results on controlled environments showing an efficiency potential of about 60% [113] for all PM, and a target to reach similar effectiveness in reducing PM on the road as well. Filters can either be a part of the original equipment of new vehicles, or they can be easily installed to existing vehicles. Importantly, in the case of brakes, filter servicing can be performed along with standard brake maintenance [114].

Promising as they may appear, according to consultation with experts, the prototype brake and tyre filters that have been developed are still often seen as less favourable measures due to brake/tyre performance and safety concerns (e.g. interference of active filters with basic brake functions or increased thermal load of the disc [115]. Literature findings suggest that it is possible to minimise or avoid these issues by optimised filter design [116], but most devices are still under development and are characterised by low technology and market readiness levels (TRL and MRL). From a financial perspective, the cost of such devices is expected to be in the order of about 200 euros per vehicle [24]. Moreover, depending on the filter type, the filters of the emission filtration device also require to be changed as often as the brake pads. As such, brake and tyre filters will come with an additional cost, which may be unappealing to key stakeholders like fleet owners and public transport operators.

Although at present policymakers do not have a direct high impact on the adoption of particle filtration devices, it could be useful in the long-term to incentivise more research and development activities, as well as promote their anticipated benefits against NEEs e.g. through public awareness campaigns to ensure a smooth, gradual and widespread integration when the technology and market are ready.

C2. Street cleaning

Includes sweeping, washing with water or dust suppressants [117], or both, and is a measure targeting primarily road dust resuspension. Sweepers alone have proven to be ineffective in capturing PM_{10} particles, and in some cases may even worsen PM pollution locally due to additional resuspension caused by the cleaning vehicle [96]. Washing on the other hand, especially with plain water, is very efficient in reducing road dust, as the water adheres to PM particles, making them heavier and keeping them from becoming airborne. Even after drying out, some particles might stick together in the form of aggregates, making them less likely to lift into the air. Street washing has been successfully applied to many cities (e.g. Düsseldorf, Stockholm, Madrid etc.), with the reported PM reduction efficiencies varying a lot, from about 6% to as high as 90%, due to a number of affecting factors like environmental conditions, amount of deposited PM dust, washing frequency, road materials, the extent of the road surface being washed, and the interference of other PM sources.

Although street cleaning is a measure that can be easily implemented in the short term by local governments at the city level and is unlikely to raise any oppositions, its main disadvantage is that its effect has been found to wear off significantly with time, in some cases after just the first 8 hours of treatment [116]. Moreover, a very important barrier to the wide application of street washing is the amount of water required, generally about 1 litre per square metre, as well as the possible consequence of increased pollution in natural water systems and sewage infrastructures, and the risk that drainage systems may not have the capacity to cope with additional water, leading to more discharges into natural water sources. These make it necessary for any consideration of implementing this measure to simultaneously consider how water pollution will be combatted. All in all, street washing can be very valuable as a complementary measure against NEE in urban environments, especially in southern European cities during hot, dry periods or incidents of desert dust transport [116].

C3. Road run-off treating

Refers to measures against rainwater runoff, which can wash PM particles off road surfaces and transport them into other environmental areas. In urban environments, run-off water usually ends up in sewers through the road drainage systems, whereas rural roads and highways are typically not connected to these networks, and road run-off often flows directly into natural water sources (lakes, rivers etc.). Since the amount of particulate matter on the roadway depends on multiple factors like location, time, traffic volume, environmental and driving conditions, PM concentrations in road run-off can vary widely [118].

In urban environments, measures against road run-off include the implementation of various water treatment solutions, often connected to the central wastewater treatment plants in order to minimise their load, especially under heavy rain conditions. The efficiency of these systems in removing suspended particles ranges from 10% to as much as 100%, depending on the technology and maintenance practices. However, these systems were not originally designed to capture non-exhaust particles specifically, and extending their application can be challenging since the required changes in infrastructure might not be feasible or cost-effective [118]. Therefore, more research is needed in the field to draw a conclusion on the benefits and overall feasibility of road run-off treating in the medium to long-terms in cities like London.

Key finding #5.5: It is possible to capture NEEs once emitted through particle collection devices but there are limits to their effectiveness, cost is likely to be a barrier to large scale uptake and, in the case of vehicle particle collection devices there could be safety/ performance issues.

The increased awareness of the importance of NEEs, and their proportional increased impact on urban air quality as exhaust emissions reduce highlights the urgent need for effective regulations, innovative technologies, and collaborative strategies to reduce their contribution to air pollution. This chapter has outlined key interventions, providing a foundation for sustainable urban environments and compliance with air quality standards. In the following chapter, a modelling analysis of selected measures has been conducted, focusing on their potential implementation in the city of London, offering practical insights into balancing environmental, economic, and social considerations.

6 Scenario-based modelling in London

This chapter evaluates the health benefits and cost-effectiveness of various interventions aimed at reducing particulate matter (PM) emissions from road transport in cities. The city of London has been used as a case study, but learnings can be applied to other European cities. A cost-benefit analysis (CBA) is applied to assess whether the societal health benefits achieved by reducing PM emissions—through interventions targeting non-exhaust emissions (NEEs) either at the source (via travel behaviour changes or technical solutions) or once emitted—exceed the associated costs of implementation. The ultimate goal is to determine the net societal benefits of these interventions and their viability as cost-effective measures to mitigate the health and environmental impacts of NEEs in cities like London.

6.1 Methodology and scenario selection

A. Baseline

The baseline scenario follows the London Atmospheric Emissions Inventory (LAEI) 2019 fleet composition and activity data, extended to 2050 using the UK trends of SIBYL baseline [119]. It estimates PM emissions from road transport, distinguishing between exhaust and non-exhaust sources, across London's geographical zones. In 2019, 44 billion vehicle kilometres were driven in London, with 97% from light-duty vehicles (LDVs) and 3% from heavy-duty vehicles (HDVs). Most kilometres were driven in outer London (48% LDVs, 42% HDVs), followed by the non-GLA zone (33% LDVs, 38% HDVs), inner London (18%), and central London (1-2%). Figure 21 illustrates this.

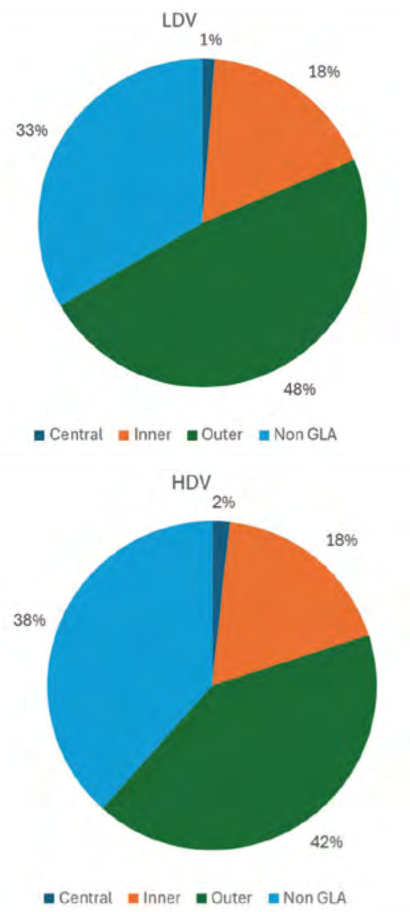


Figure 21: Allocation of kilometres driven per London zone in 2019: (top) light-duty vehicles; (bottom): heavy-duty vehicles.

Fleet electrification is projected to increase significantly for LDVs, from 0.4% in 2019 to 42% by 2030 and 86% by 2050, while electrification for HDVs will be slower, reaching only 15% by 2030 and 53% by 2050 as illustrated in Figure 22. Car usage remains highest across all zones but is significantly lower in central London (29% vs. 63%-75% in other zones), suggesting a greater reliance on alternative transport options in the city centre (Figure 32 in the Annex). By 2050, total kilometres driven in London are expected to exceed 51 billion, reflecting a gradual increase from 44.6 billion in 2019 to 48 billion in 2030. These baseline projections serve as the reference point for assessing intervention scenarios.

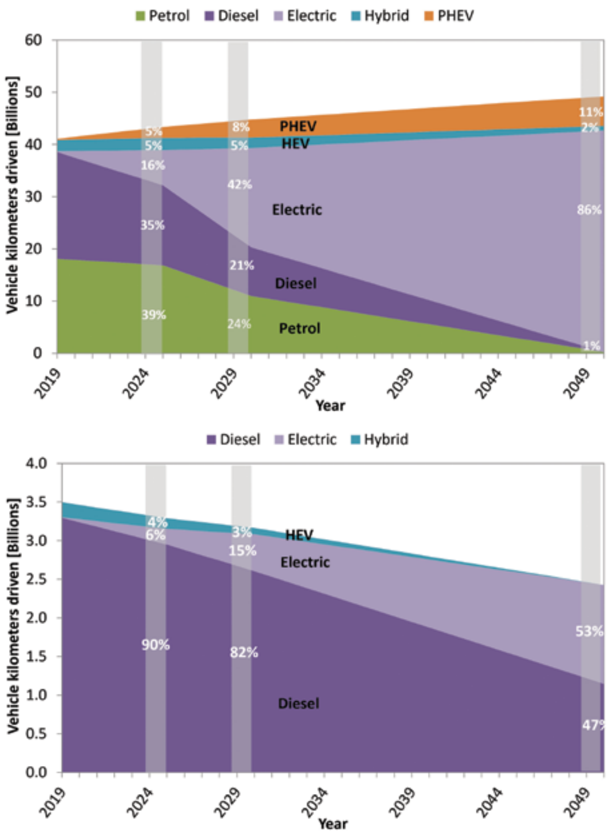


Figure 22: Evolution of the kilometres driven and fleet composition in London to 2050:(top) LDVs; (bottom) HDVs.

B. Cost-benefit analysis and Scenarios

Cost-benefit analysis (CBA) is a widely used method for evaluating policy interventions by comparing societal costs and benefits in monetary terms. In this study, the CBA framework assesses whether the benefits of an intervention reducing non-exhaust emissions (NEEs) in London outweigh implementation costs over a defined time horizon. The assessment also considers cost-effectiveness by calculating the cost per kg of PM_{10} and $PM_{2.5}$ saved, identifying scenarios with the highest net benefit or best cost-effectiveness.

The CBA follows a structured methodology:

1. **Fleet projections** – Based on the LAEI 2019 baseline extended up to 2050, as illustrated in section A.
2. **Emission reductions** – Calculated for each intervention relative to the baseline scenario.
3. **Monetized benefits** – Using external damage cost values from UK [5] and EU [4] reports.
4. **Implementation costs** – estimations performed only where available, accounting for operational, maintenance, and depreciation costs.
5. **Net benefits & cost-effectiveness** – Comparing monetized benefits against costs, with cost-effectiveness defined as cost per unit of pollutant mass reduced.

A flowchart of the CBA calculations (Figure 23) illustrates this methodology, encompassing fleet projections, emission reductions, monetized benefits, and net benefit calculation.

The analysis builds on established methods, including applications in the Euro 7 Impact Assessment Study [24]. To account for future economic conditions, a 3% social annual discount rate and 1% annual inflation are applied beyond 2025.

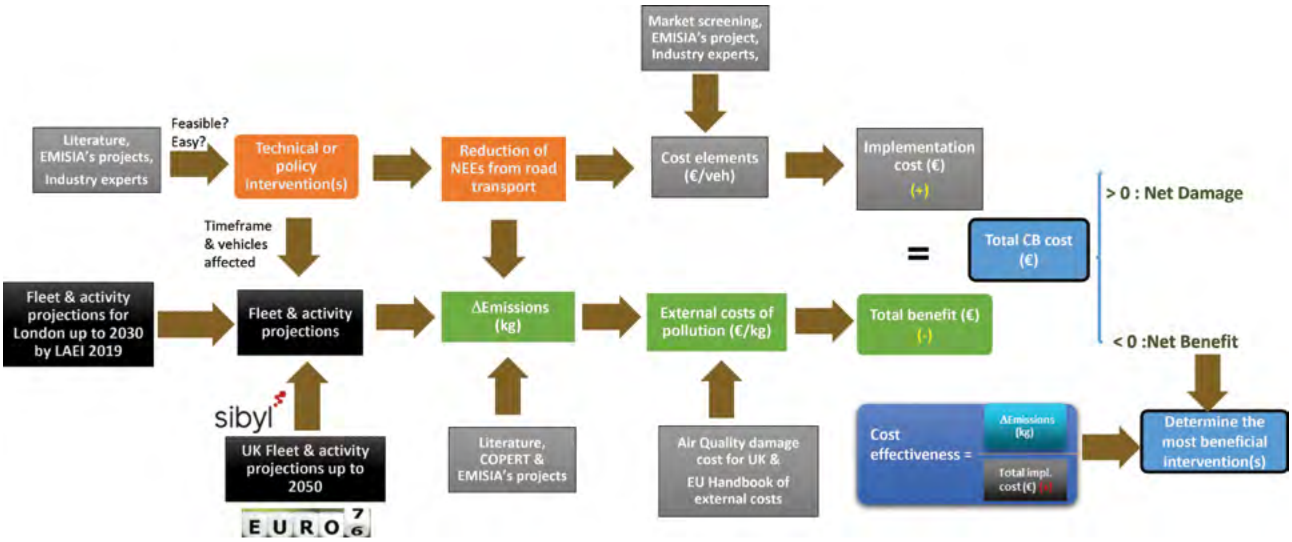


Figure 23: Flowchart of the CBA methodology for each scenario.

The final CBA scenario selection was based on an evaluation of 13 potential interventions (detailed in section 5.2), considering factors such as efficiency, ease of implementation, stakeholder involvement, and societal cost (where available).

The following three scenarios were chosen, based on their relevance and available quantitative data for modelling:

- **Scenario 1:** Wear-Resistant Brake Components – Introduces low-wear braking materials (i.e. alternative braking pads and discs) in all new vehicles. This is a technical type of intervention that reduces NEEs at source. Since there are already many solutions for “low emitting” braking pads and discs developed by OEMs with high technology readiness and market readiness levels (TRL and MRL) due to the established Euro 7 brake wear limits, this scenario can easily be applied to all new vehicles in short-term. In this analysis, low-emitting pads have been considered with an efficiency of around 60% and an additional cost of 90 Euro over lifetime for LDVs. 5.3Due to high initial costs and compatibility issues in old vehicles, retrofitting existing vehicles is not considered.

- **Scenario 2:** Brake Particle Collection Devices – Implements brake filtration systems for all new vehicles. This is a technical type of intervention that captures non-exhaust particles at source. While highly efficient, these technologies currently have low TRL and MRL and have a higher cost than the alternative low-emitting braking components examined in scenario 1, making them a long-term intervention. For a fair comparison in the CBA, the same introduction date as Scenario 1 is assumed. More details on these devices have been explained in chapter 5.3.
- **Scenario 3:** Combined Wear-Resistant Brake & Tyre Components – Was chosen to combine both wear-resistant brake and tyre components for two key reasons. First, the Euro 7 regulation sets emission limits for both brake and soon, for tyre wear, making it logical to assess their combined impact. Second, this scenario expands scenario 1, which focuses solely on brake wear-resistant components to new vehicles, by incorporating wear-resistant tyres to both new and existing vehicles. Recent findings from the 2024 European Commission study [40] highlight that wear-resistant tyres can further complement low-wear braking materials in reducing total NEEs with very low additional cost since these tyres already exist in the market and there is no need for different or more costly materials for reduced tyre wear [13]. While these components can be implemented separately, their simultaneous adoption could maximize PM reduction benefits and ensure regulatory compliance in the long term. Both of them are technical types of interventions that reduces NEEs at source.

There is sufficient quantitative data available for the accurate modelling of these three scenarios in the CBA. They also directly affect vehicles (new or existing), ensuring a more precise evaluation. To ensure a fair comparison, all scenarios are assumed to be introduced gradually from 2026 (2028 for low wear tyres), aligning with the Euro 7 regulation's brake and tyre wear limits. Table 3 summarizes the key parameters of each scenario, including intervention timeline, efficiency, and per-vehicle implementation costs (excluding taxes and profit margins).

It should be noted that most data for efficiency and costs of each intervention are for LDVs while for HDVs the uncertainty is still high, as already mentioned in Chapter 5.3. However, HDVs are high emitters and cannot be excluded from the study. Therefore, assumptions and extrapolations have been done for HDVs where needed in the CBA.

The final cost-saving estimations come with some uncertainty due to lack of accurate and up-to-date data on the efficiency and cost of each intervention, particularly for heavy-duty vehicles. A summary of all interventions is presented Table 19 of the Annex.

Table 3: Selected scenarios examined in the cost-benefit analysis.

Scenario ID	Description	Vehicles applied	Timeline	Efficiency per veh (%)	Avg. cost per veh (EUR)
S1	Low emitting brakes	New	Gradually from 2026	Brakes: 62% for PM_{10} (reduced to 55% for $PM_{2.5}$)	90 (LDVs)
S2	Particle filtration devices from brake wear	New	Gradually from 2026	Brakes: 79% for PM_{10} (reduced to 72% for $PM_{2.5}$)	160 (LDVs)
S3	Low emitting brakes & tyres	New (for brakes) All (for tyres)	Gradually from 2026 for brakes & 2028 for tyres	Brakes: 62% for PM_{10} (reduced to 55% for $PM_{2.5}$), Tyres: 10% less PM_{10} & $PM_{2.5}$	Costs of S1 + cost for Tyres: 2 (cars) to 100 (HDVs)

C. Benefit analysis and Scenarios

For some policy & management interventions, cost data is unavailable or highly uncertain, making a full CBA unfeasible (i.e. extra infrastructure costs, consumer costs, regulatory costs, etc.). Instead, a benefit analysis (BA) is conducted, assessing PM emission reductions and associated societal benefits without implementation cost considerations. The following scenarios that reduce NEEs at source by changing travel behaviour were selected based on available quantitative data and their potential to reduce NEE amongst other things:

- **Scenario 4:** Accelerated Fleet Electrification – Assumes 100% electrification of the whole vehicle fleet by 2050 and TfL buses by 2030 (in alignment with the Mayor of London's ambition), maintaining the same mobility needs (vehicle kilometres) as the baseline for a fair comparison. Incremental cost for society is not considered, since on the one hand, it is difficult to estimate the extra cost needed for the infrastructure or the incremental cost for the owner over time and, on the other hand, it is not fair to assign all costs of electrification in CBA since we only focus on the benefits from the reduction on PM emissions (excluding the benefits from reduction of greenhouse gases and other air pollutants).
- **Scenario 5:** Travel Behaviour Shift – Models a 33% reduction in passenger car vehicle kilometres travelled by 2041 (compared to 2015) in alignment with the Mayor's Transport Strategy (MTS) [120], promoting public transport (25% increase in bus kilometres by 2041), cycling, and walking. Costs for achieving this modal shift is hard to be accurately assumed and this is why only the benefit is examined in the analysis.
- **Scenario 6:** This is the combined scenario of scenario 4 and 5 to address the simultaneous impacts of both faster fleet electrification and modal shift from cars to public transport on NEE.

To ensure a fair comparison, all scenarios are assumed to be introduced gradually from 2026. Table 4 summarizes the key parameters of each scenario, including intervention timeline and efficiency per vehicle.

Table 4: Selected scenarios examined in the benefit analysis.

Scenario ID	Description	Vehicles affected	Timeline	Change compared to baseline
S4	Accelerated fleet electrification	All	Applied from 2026	100% electric vehicles by 2050 (baseline: LDVs 86% & HDVs 53%) & 100% electric buses by 2030 (baseline: 67%) aligned with MTS
S5	Modal shift from cars to public transport	Cars, Buses	Applied from 2026	33% less vkm by cars & 25% more by buses in 2041 compared to baseline aligned with MTS
S6	Modal shift from cars to public transport & Faster fleet electrification	All	Applied from 2026	As per scenario 4 and 5 together

6.2 Scenario results

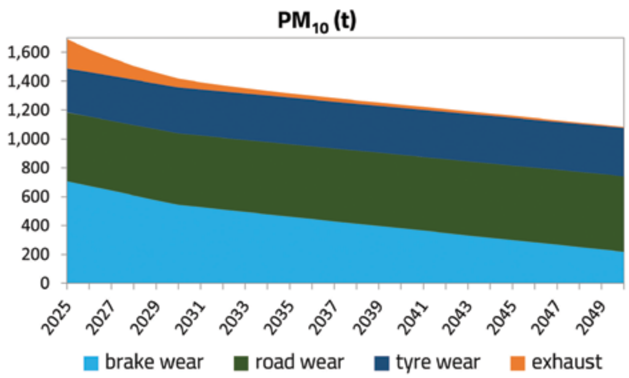
A. Baseline

The anticipated evolution of the vehicle kilometres driven and fleet composition in London until 2050 (Figure 22) is combined with the state-of-the-art emission factors (in g/km) per source and vehicle type (Table 2) to estimate the projected PM emissions from road transport. Figure 24 presents the evolution of PM_{10} and $PM_{2.5}$ and its breakdown by source (brake wear, tyre wear, road wear and exhaust) under the baseline scenario, assuming no further action is taken. Currently, NEE already account 88% of total PM_{10} and 85% $PM_{2.5}$ emissions in 2025. This trend will continue due to the growing penetration of electric vehicles (EVs) and the dominance of modern Euro-standard internal combustion vehicles equipped with particulate filters.

At present, brake wear is the dominant source of NEE since they represent 48% of total PM_{10} and 42% of total $PM_{2.5}$ emissions followed by road wear (32% and 38% respectively) and tyre wear (21% and 19% respectively). However, this distribution is expected to shift over time. While brake wear emissions will decrease, tyre and road wear emissions will increase, driven by the uptake of heavier vehicles such as sport utility vehicles (SUV) [121] and EVs. As highlighted in chapters 3 and 5.3, electric vehicles produce around 83% less brake emissions than the equivalent conventional ones due to regenerative braking, but their increased weight leads to 20% higher tyre and road wear emissions. By 2050, road and tyre wear will account for almost 80% of total PM emissions (both for PM_{10} and $PM_{2.5}$ emissions), while exhaust emissions will shrink to just 1% of total PM emissions.

The remaining 20% will be attributed to brake wear. This shift underscores the increasing significance of tyre and road wear emissions in the future, reinforcing the need for targeted interventions beyond exhaust emission controls.

Key finding #6.1: Tyre and road wear emissions will dominate future PM pollution. While exhaust emissions are expected to vanish and brake emissions to decline due to fleet electrification, tyre and road wear will become the dominant sources of non-exhaust emissions (NEE) by 2050. This highlights the growing need for targeted interventions beyond traditional exhaust emission regulations.



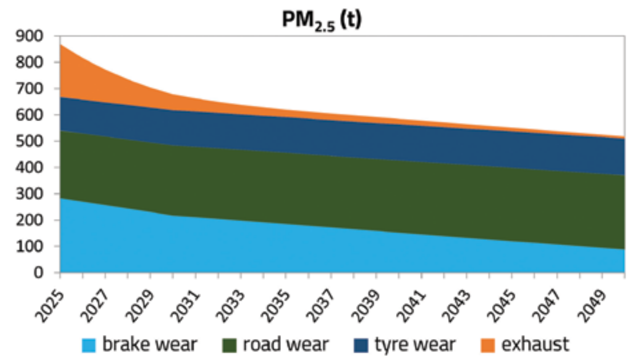


Figure 24: Expected evolution of PM from road transport per source in London in 2050 without any further action (baseline scenario). Results calculated based on state-of-the-art emission factors: (top) PM_{10}; (bottom) $PM_{2.5}$.

B. Cost-benefit analysis and Scenarios

The projected evolution of PM emissions from NEE sources is calculated for all three CBA scenarios (as defined in section 6.1) up to 2050. Figure 25 presents the PM savings against baseline scenario (i.e. no additional NEE reduction measures). Since exhaust emissions are not affected by these interventions and fall outside this study's scope, they are excluded from the CBA analysis. Among the scenarios, scenario 2 (brake filtration devices) achieves the greatest cumulative PM savings reaching 4635t of PM_{10} to 2050 with 1690t of them being $PM_{2.5}$. This is closely followed by scenario 3 (low-wear brakes and tyres), which achieves 4260t of PM_{10} with 1552t of them being $PM_{2.5}$ savings. When only low-emitting brakes are considered (scenario 1), the PM savings are limited to 3638t for PM_{10} with 1291t of them being $PM_{2.5}$.

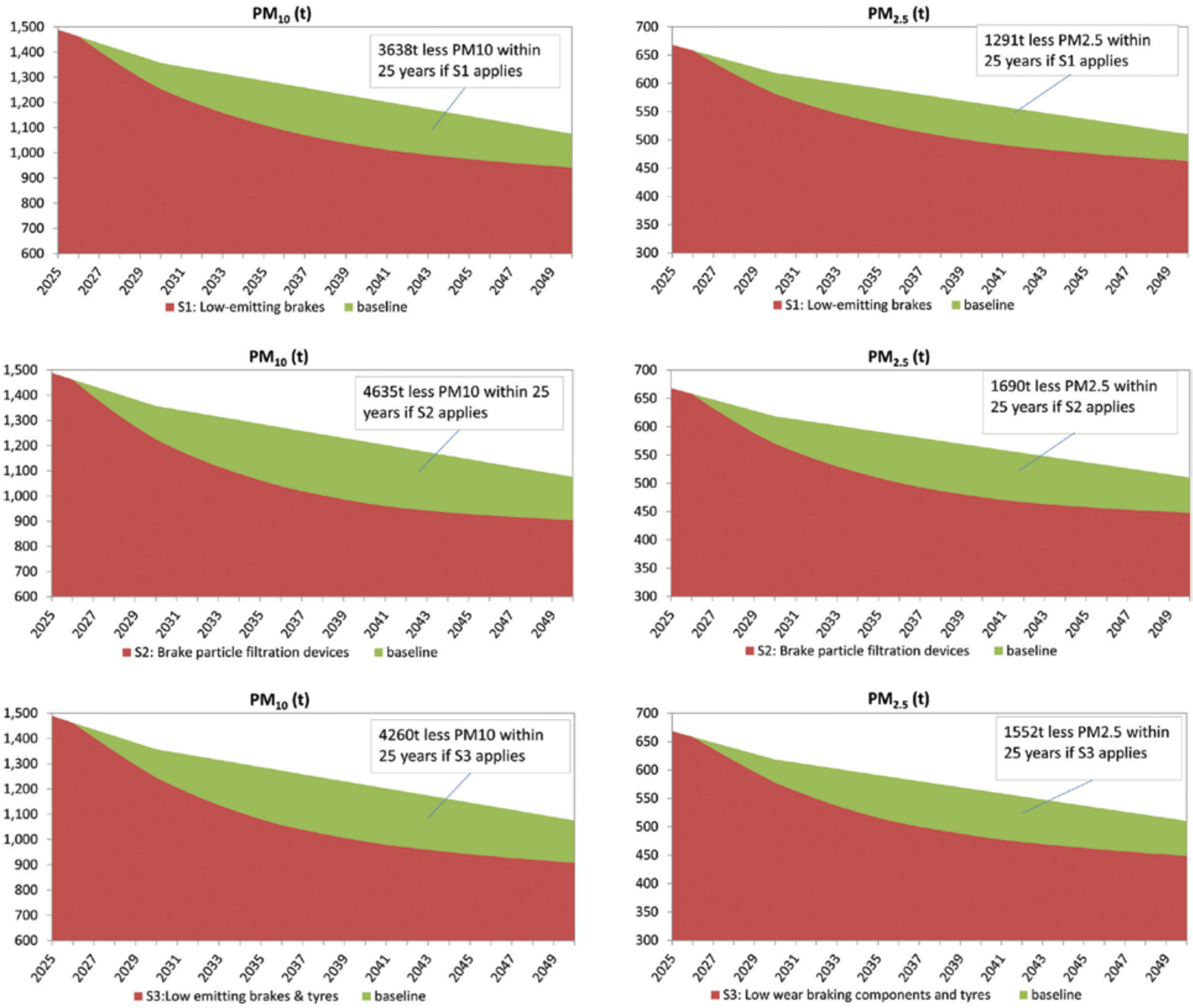


Figure 25: Evolution of PM from non-exhaust sources in London and PM savings from each scenario compared to baseline: (Left) PM_{10}; (Right) $PM_{2.5}$.

Figure 26 visualizes the PM reduction trends for all scenarios over time, allowing direct comparison.

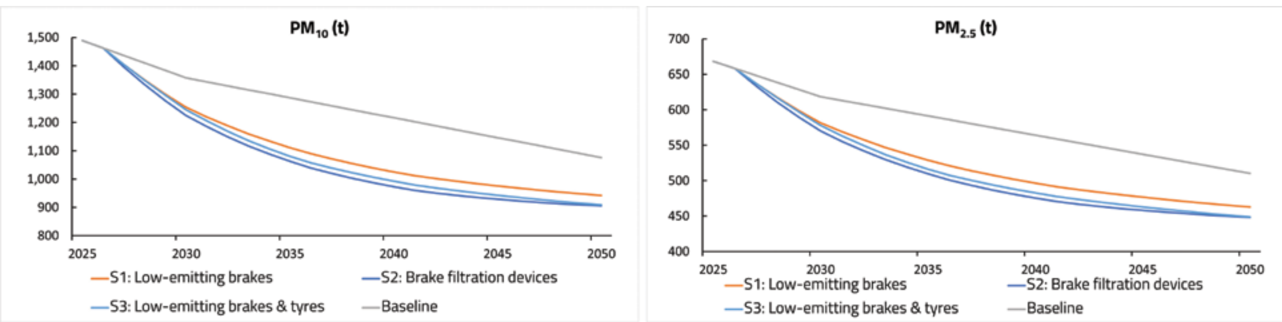


Figure 26: Comparison of evolution of PM from non-exhaust sources in London among different scenarios: (Left) PM_{10}; (Right) $PM_{2.5}$.

While Figure 25 and Figure 26 presented the potential emission savings for each scenario, a cost-benefit analysis (CBA) requires monetization of the environmental benefits and comparison against the associated implementation costs. Using the damage costs for PM_{10} and $PM_{2.5}$ in London from the Air Quality damage cost for UK [5], the PM_{10} and $PM_{2.5}$ reductions are converted into monetized benefits.

Figure 27 illustrates the difference between benefits and costs over time for the three scenarios, with values discounted over net present value (NPV) for fair comparison. Initially, all scenarios incur high costs, leading to net damage in early years. However, all scenarios achieved net benefits well before 2050.

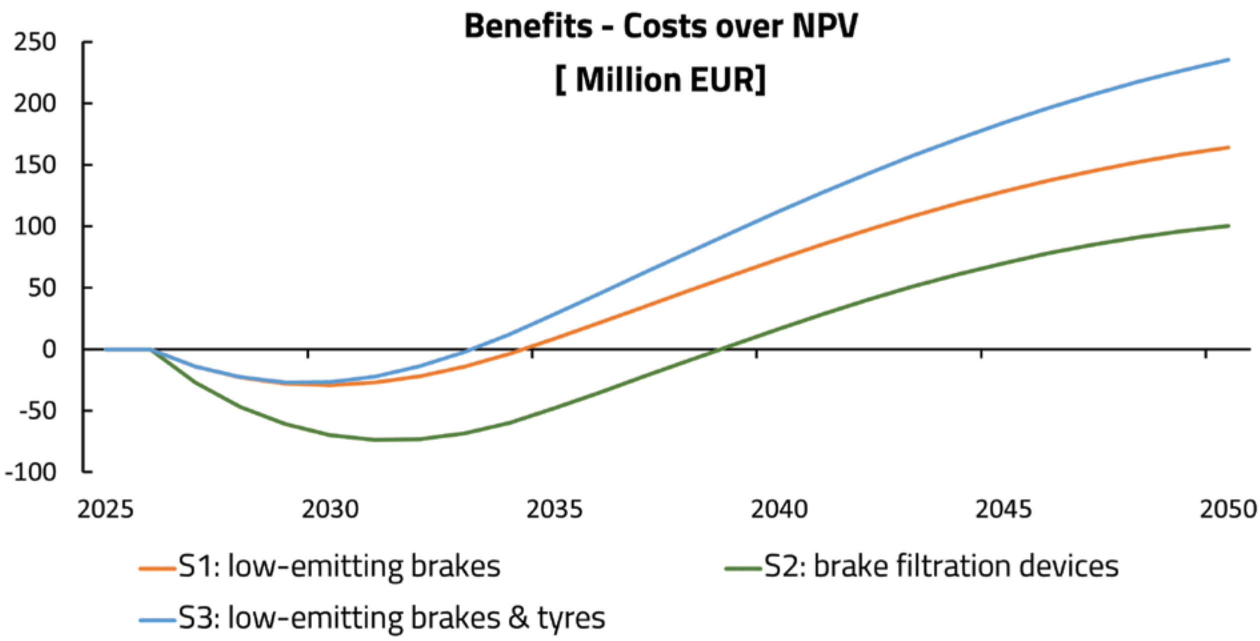


Figure 27: Evolution of net benefit until 2050 from the application of each scenario in London. Values are discounted over NPV.

The most beneficial scenario is determined from Figure 28, which integrates the net benefit curve from Figure 27, representing the cumulative net benefits from 2026 up to 2050. The results indicate that scenario 3 (low emitting brakes and tyres) is the most beneficial scenario with a cumulative net benefit of 235 million Euro, demonstrating the added value of combining brake and tyre interventions. Then, scenario 1 (low emitting brakes) follows with a net benefit of 164 million Euro, meaning that incorporating low-wear tyres (scenario 3 vs. scenario 1) yields an additional 71 million Euros, mainly due to their low extra cost ("low-emitting" tyres are already in the market, requiring no additional R&D costs [13]). The less beneficial scenario was proven to be scenario 2 (brake filtration devices) with net benefits of 100 million Euro within a 25-year time frame. This is due to higher costs of filtration devices compared to simply replacing high-emitting brake components (e.g., LS pads or GCI discs) with low-emitting alternatives (e.g., NAO pads or optimized discs).

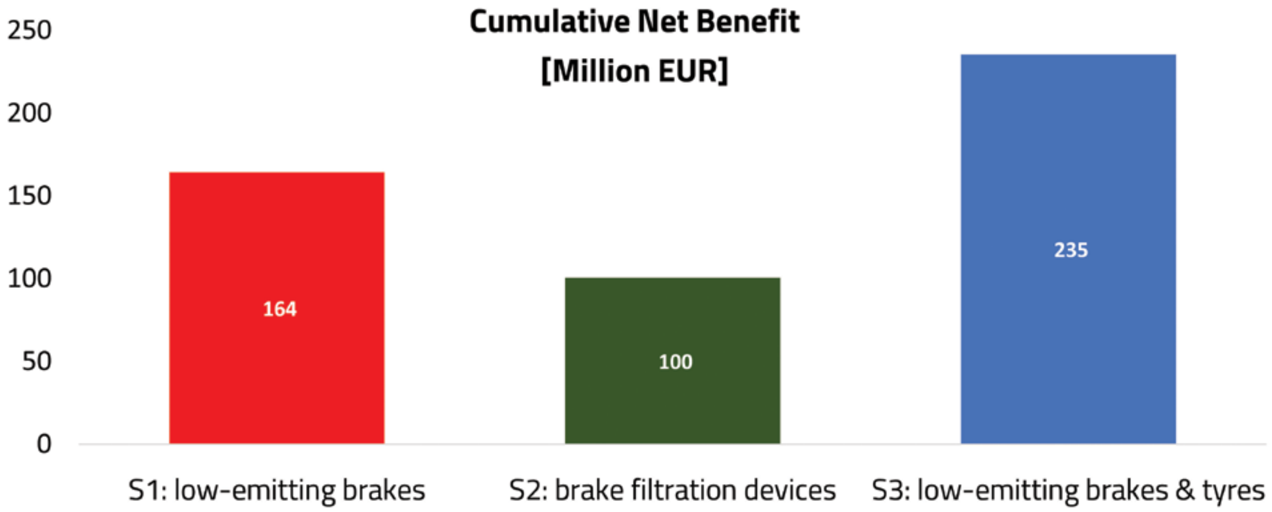


Figure 28: Cumulative net benefit from 2026 until 2050 for each scenario. Values are discounted over net present value (NPV).

Beyond cumulative net benefits, there are two more indicators that are commonly used to assess scenarios in a CBA. The first one is the benefit over cost ratio (BCR), a key indicator used to determine whether an intervention is economically viable compared to the baseline. The BCR is an indicator that summarizes the overall relationship between the relative costs and benefits of the examined scenario. A ratio above 1 indicates a beneficial intervention. Scenario 3 (low-emitting brakes and tyres) achieves the highest benefit over cost ratio of 1.71, demonstrating its viability at the assumed cost. Then, scenario 1 (low wear braking components) follows closely with 1.68 and scenario 2 (brake particle collection devices) with 1.23, reflecting its higher cost per unit of benefit. This is illustrated in Table 5 together with the cost-effectiveness indicator.

The cost-effectiveness indicator measures the total implementation cost needed for saving one kilogram of total wear or PM_{10} or $PM_{2.5}$. The lower the investment costs (for the society) that are needed for achieving one kilogram of PM_{10} or $PM_{2.5}$ the better.

The results for the case of London show that scenario 1 (low-emitting brakes) requires the least cost per kilogram of PM_{10} and $PM_{2.5}$ saved. When addressing cost-effectiveness among total wear, scenario 3 (low-emitting brakes and tyres) is over three times more cost-effective than scenario 1 and four times more than scenario 2. This is due to high tyre wear levels, since most of tyre wear particles are larger than PM_{10} so they are not entirely released into the atmosphere as airborne PM but lay on the road and can be harmful for the water and soil pollution as discussed in chapter 3.3.

Key finding #6.2: Among the three scenarios evaluated through a full cost-benefit analysis (CBA), combining wear-resistant brake and tyre components offered the highest net benefits (235 million Euro) and the best benefit-to-cost ratio (1.71). This highlights the significant gains achievable through relatively low-cost technical solutions already available in the market.

Table 5: Ratios of benefit over cost and cost-effectiveness. The scenario with the highest benefit / cost ratio is the most beneficial and the scenario with the highest cost-effectiveness is the one with the lowest investment needed for achieving a certain level of PM savings.

CBA indicators	S1: low-emitting brakes	S2: brake filtration devices	S3: low-emitting brakes & tyres
Benefits / Cost ratio	1.68	1.23	1.71
Cost-effectiveness $PM_{2.5}$ [EUR/kg]	186,103	252,732	213,222
Cost-effectiveness PM_{10} [EUR/kg]	66,036	92,135	77,687
Cost-effectiveness total wear [EUR/kg]	66,036	92,135	20,224

C. Benefit analysis and Scenarios

The projected PM reductions from NEE sources up to 2050 have been also calculated for the benefit analysis scenarios, i.e. scenario 4: accelerated fleet electrification, scenario 5: modal shift from cars to public transport, and scenario 6: accelerated fleet electrification & modal shift from cars to public transport. These scenarios, as defined in section 6.1, are compared to the baseline scenario which represents the business-as-usual scenario with no additional NEE reduction measures.

Figure 29 illustrates the PM_{10} and $PM_{2.5}$ savings achieved in these scenarios. Scenario 5 (modal shift from cars to public transport) achieves the greatest cumulative PM savings, reducing 5548t of PM_{10} by 2050 with 2610t of them being $PM_{2.5}$. Scenario 4 (Accelerated Fleet Electrification) yields significantly lower reductions due to the negative impact of electrification on tyre and road wear emissions, which remain dominant sources of PM. When both accelerated fleet electrification and modal shift from cars to public transport are applied simultaneously (scenario 6), the total savings are slightly less than 99% of the sum of the individual savings from scenarios 4 and 5, indicating a small overlap in their effects.

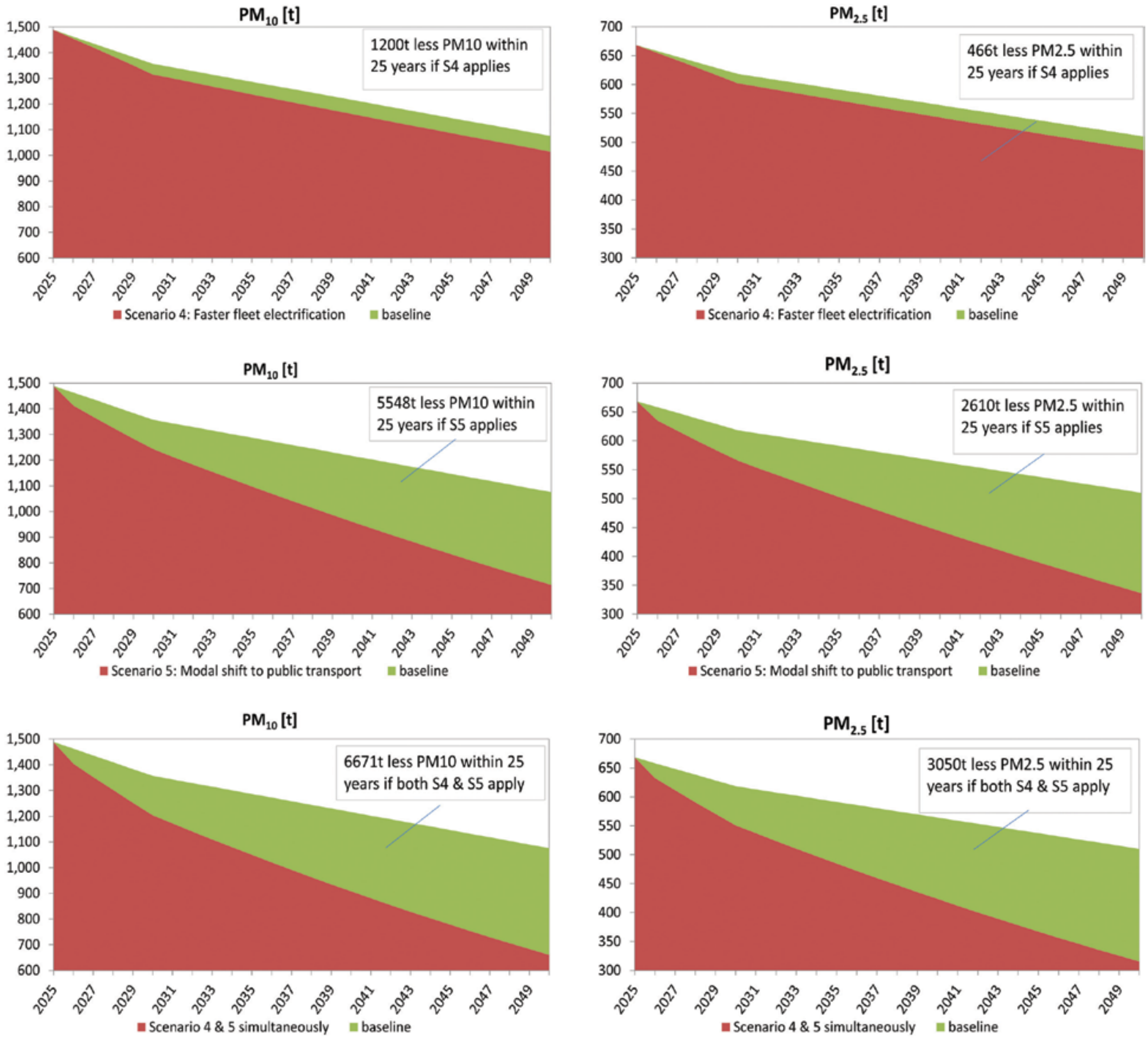


Figure 29: Evolution of PM from non-exhaust sources in London and PM savings from each scenario compared to baseline: (Left) PM_{10}; (Right) $PM_{2.5}$.

For these policy scenarios, only benefit analysis (BA) is conducted, as estimating the total implementation cost poses significant challenges. To monetize the environmental PM savings, the damage cost values for London [5] are applied. The resulting benefits over time are presented in Figure 30 and cumulatively from 2026 to 2050 in Figure 31 ranging from 194 million Euro for the scenario of accelerating fleet electrification up to 951 million Euro when the targets for modal shift from cars to public transport is also applied on top of accelerating fleet electrification.

All values are discounted over net present value (NPV) to allow a fair comparison. These findings highlight that promoting a shift away from private cars to public transport is the most effective strategy for reducing PM emissions from NEE sources in London.

Key finding #6.3: Modal shift from cars to public transport has the greatest potential for reducing NEE. The benefit analysis (BA) revealed that shifting travel behaviour from cars to public transport delivers up to five times greater PM emission reductions than fleet electrification alone (excluding the benefits of electrification for exhaust emissions). This underscores the importance of policies promoting public transport, cycling, and walking in tackling urban air pollution.

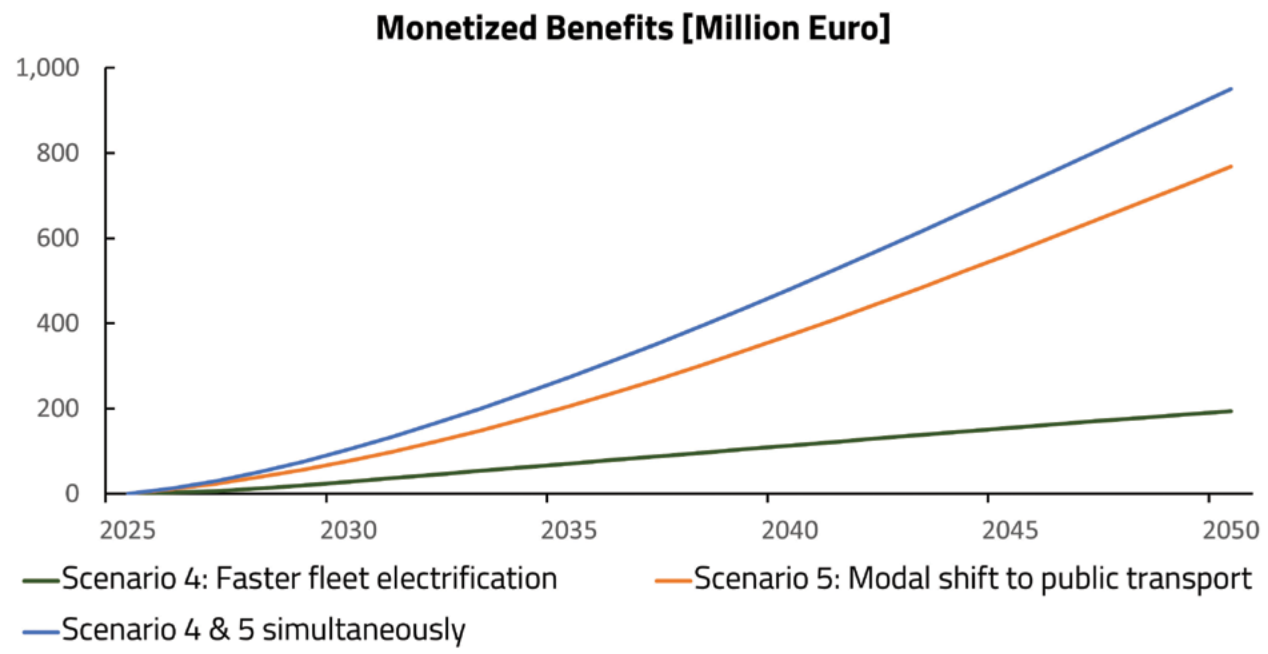


Figure 30: Evolution of monetized benefit until 2050 for three different policy scenarios in London. Values are discounted over NPV.

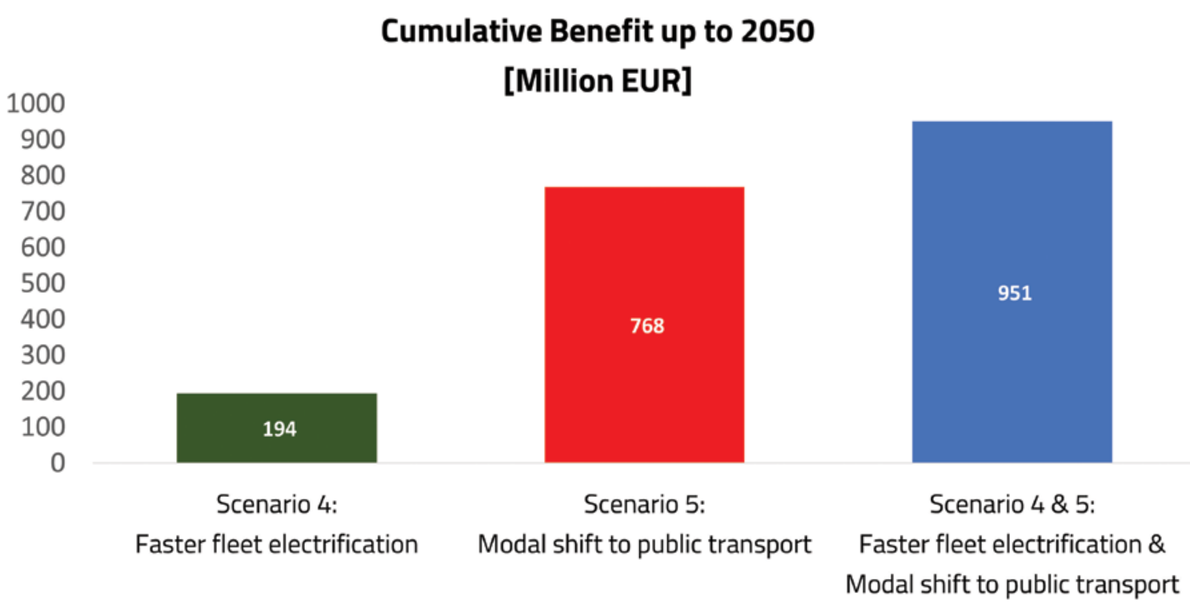


Figure 31: Cumulative benefit from 2026 until 2050 for three scenarios. Values are discounted over net present value (NPV).

D. Scenario conclusions

This chapter highlights the significant societal benefits of various interventions aimed at reducing non-exhaust emissions (NEEs) in London. Based on the data availability for efficiency and cost of each intervention analysed in chapter 5.3, three scenarios were selected for a full cost-benefit analysis (CBA): Scenario 3 (Low-Emitting Brakes & Tyres) emerged as the most cost-effective, offering the highest benefits and best benefit-to-cost ratio. In addition to these, two further policy scenarios—accelerated fleet electrification and modal shift from cars to public transport—were assessed, both individually and combined.

While these policy scenarios align with the Mayor's Transport Strategy (MTS) and demonstrate significant societal benefits, a full cost-benefit analysis (CBA) was not conducted due to the complexity and uncertainty in estimating total implementation costs, including infrastructure investments and indirect societal costs. However, the benefit analysis (BA) provides valuable insights into their effectiveness in reducing NEE emissions, particularly highlighting the substantial impact of modal shift from cars to public transport (either alone or combined with fleet electrification). Detailed scenario results are available via a publicly accessible Microsoft Power BI. These findings serve as a valuable foundation for shaping future policies, with potential refinements as new data and technologies emerge.

7 Conclusions and recommendations for policymakers

Non-exhaust emissions (NEEs) from road transport, including brake, tyre, and road wear, have emerged as a significant contributor to particulate matter (PM) pollution with considerable environmental, health and economic consequences in urban areas like London. The high content of toxic elements and compounds in PM, especially micro-plastics and black carbon, pose severe health risks, such as respiratory and cardiovascular diseases, as well as significant contamination of the air, water, and soil environments. Therefore, NEEs from road transport currently constitute a critical focus area for effective mitigation strategies. However, with the exception of Euro 7, which will for the first time set limits for brake and tyre wear emissions, NEEs are not regulated. To this end, the proven effectiveness of policies such as Low Emission Zones (LEZs) against exhaust emissions, particularly PM, is pointing towards expanding existing regulations and interventions to include NEEs, or even develop new ones to tackle brake, tyre, and road wear specifically.

In this study, a thorough market screening, a series of bilateral discussions with industry experts, and a dedicated workshop with key stakeholders were carried out, to recognise and evaluate the most effective potential interventions against NEEs. Subsequently, a cost-benefit analysis (CBA) framework was used to assess whether the benefits of an intervention reducing non-exhaust emissions in London outweighed implementation costs over a defined time horizon. Three scenarios were selected to be analysed for a full cost-benefit analysis, with the one combining low-emitting brakes and tyres emerging as the most cost-effective, with the highest benefits and benefit-to-cost ratio.

Its benefits are about 1.5 higher than the second most efficient scenario (low-emitting brakes) and about 2.5 times higher than the third most efficient one (brake filtration devices). All three scenarios resulted to substantial net benefit. Two more policy scenarios, the accelerated fleet electrification and the modal shift from cars to public transport, were also examined both individually and together. For these scenarios only a benefit analysis was performed since their cost could not be quantified. In this case, too, the combined effect of the two scenarios resulted in the highest net benefit, around 1.5 times higher than the second most efficient scenario (mode shift to public transport) and about 5 times higher than faster fleet electrification.

Even though many European cities like London, Barcelona, and Milan have recognized NEEs as often the primary source of PM pollution, particularly in the case of light-duty vehicles (LDVs), there are still significant knowledge gaps around the subject, for example:

- A considerable lack of data on particle chemical composition, the emission rates from different sources (e.g., brake, tyre, and road wear), as well as the way environmental factors, driving behaviours and different components and materials influence the dispersion of the emissions.
- The variability in the NEE data that do exist in terms of collection, processing and reporting, which underscores the need for more robust research and collaborative efforts to understand the sources, chemical composition, and toxicity of these emissions.
- The inconsistent or improper monitoring of NEEs across European cities, which remain a barrier to effective policymaking.

Closing these gaps will enable the development of more targeted and effective strategies but waiting until the knowledge gaps have been addressed should not prevent action; there are still policies that can and should be implemented immediately to minimise potential harm, even if all factors are not yet fully understood.

To advance efforts to reduce NEEs, the following recommendations are proposed, based on our evaluation of the most effective potential interventions carried out in Section 5.3, and the cost-benefit and benefit analyses (CBA and BA) performed in Chapter 6:

Recommendations at a local level

This group of recommendations includes interventions against NEEs which policymakers are expected to be able to have a high level of involvement in and immediate impact on, utilising the findings in Chapter 5 and the cost-benefit analysis results in Chapter 6:

- It is important that policymakers recognise NEEs from road transport as one of the major sources of air pollution in their cities and incorporating NEEs into urban planning decisions. This is supported by our findings from three European metropoles (London, Milan, and Barcelona). Once this major environmental issue is recognised and quantified in other cities as well, it will be possible for policymakers to take action, first by raising awareness to everyone involved.

- It is essential that policymakers take proactive measures at the local level to tackle NEEs, as relying on Euro 7 will not be enough. The regulation applies only to new vehicles and is most likely to take decades to show full effect, therefore cities need to act immediately to reduce current emissions. Without additional local policies the improvements driven by Euro 7 will be significantly delayed, negatively impacting public health and the environment.
- NEE considerations should be added and prioritised within all urban air quality policies, including traffic management and sustainable mobility, with the goal to reduce the kilometres driven by high emitting vehicles. The most effective tools to directly influence this in the short and medium terms are the expansion of low emission zones, and the promotion of mode shift from cars to active and public transport.
- Controlling traffic volume and flow, reducing vehicle speeds and promoting smoother driving styles are additional measures, very likely to further alleviate PM pollution in the short term due to reduced brake, tyre, and road wear. However, it is important that policymakers ensure to not inadvertently incentivise the use of private vehicles when promoting these measures.
- In parallel, it is recommended to launch public awareness campaigns to educate the public on the environmental (including air, soil, and water), health, and safety benefits, and make public transport more attractive). Positive communication alongside interventions will reduce the risk of raising public opposition.
- It is recommended to put measures in place that limit or penalise heavier combustion vehicles, such as higher parking fees for sport utility vehicles (SUVs), as for example in the case of Paris [122]. SUVs accounted for 10% of new car sales in Europe in 2010, 33% in 2018, and 54% in 2024 [121]. This has led to an average mass increase of new cars of 21% over the past 20 years. As opposed to EVs, the weight and NEE increase due to still predominantly fossil fuel SUVs is not offset by zero tailpipe emissions, making it important to focus the efforts on ICEVs. Nevertheless, it is also important that EV models move from SUV to smaller sizes, too.
- Our research has concluded that fleet electrification will overall benefit NEEs, at least in urban areas where the use of regenerative braking is more extensive and significantly reduces brake wear. Taking into consideration the side benefits of EVs from decarbonisation and exhaust emissions, it is recommended that faster fleet electrification is pursued in the short term, but preferably along with vehicle lightweighting measures (e.g., weight taxation schemes, low-density materials, limited battery range/capability) to tackle the trade-off of increased weight and tyre wear and ensure that this preventive intervention results in a net positive effect for all NEE sources in the long-term.

To this end, it is proposed that policymakers shall encourage private sector involvements in tackling NEEs. For example, all commercial vehicles that run many kilometres within cities (e.g., taxis, vans, etc.), as well as public transport vehicles (e.g., buses) are electrified as soon as possible (as already stipulated within the Mayor's Transport Strategy in London in the case of buses). Providing incentives for electric vehicles (EVs) and disincentives for internal combustion engine vehicles (ICEVs) can be particularly helpful in this cause, as discussed in Section 5.3.

- We recommend that policymakers prioritise the proper maintenance of the cities' roads, as this is the most effective measure against road wear in the short term, whereas other measures like street washing, or resurfacing with wear-resistant materials might have significant trade-offs (e.g. water pollution) or not be economically feasible.
- It is recommended that technological measures are sufficiently supported by policymakers. This can be done through e.g., continuous compliance checks with Euro 7 limits via technical inspections for some regulated fleets (buses, taxis etc.) and incentives for adopting technological solutions of low-wear brake/tyre components & technologies.

Recommendations at a national level

Policymakers are expected to be able to have a medium level of involvement and an indirect impact to this group of interventions, primarily through government advocacy. The findings in Chapter 5 and the cost-benefit and benefit analyses results in Chapter 6 may be utilised for this purpose:

- Although regulations like the Euro 7 are an international action, policymakers can affect their successful implementation by the Member States, even before the new laws come into effect. This can be done by advocating for the establishment of effective and timely enforcement mechanisms, like consistent emissions monitoring and compliance testing. At the same time, increasing public awareness and supporting original equipment manufacturers (OEMs) in adapting to the new standards is also essential for the smooth, gradual integration of not only the impeding and future limits but also the new technological solutions necessary to accomplish them. Policymakers may utilize study results to advocate for evidence-based regulations.
- The promotion of wear-resistant components and materials for brakes and tyres, as well as the launch of awareness initiatives on their benefits to educate manufacturers, fleet owners and the public in general, can prove to be very helpful in not only the adoption of the Euro 7 limits for new vehicles, but also their expansion to existing vehicle fleets.

- Some strong evidence already exists on which solutions the market should be redirected at, e.g., increasing the share of drum brakes and using hard-metal coatings on grey cast iron discs, or replacing them with composite ones. However, it should be noted that these new studies and data emerging continuously and reshaping our understanding of the components with the highest overall potential to benefit the environment and the public's health and safety. For example, although NAO pads have proved to be highly effective against NEEs compared to their low-steel counterparts, there is new evidence revealing a potential trade-off of increased toxicity which needs to be investigated. Therefore, policymakers should support national research programs focused on improving the durability and performance of wear-resistant components, ensuring that new materials do not introduce unintended negative effects (e.g., increased toxicity).
- Policymakers should also encourage the establishment of national databases for tracking NEE emissions and mitigation efforts, ensuring data consistency and comparability across regions.
- The exploration of public procurement policies that prioritize low-wear vehicles and road maintenance strategies in publicly funded transport and infrastructure projects.

Recommendations at an international level

This group of recommendations includes measures that require active support by policymakers, industry, and civil society:

- It is recommended that different cities/countries engage in discussions and cooperate on the development of standard monitoring and harmonized measurement protocols for brake, tyre, and road wear emissions. This will significantly help minimise the knowledge gaps identified throughout this report, as well as make fair comparisons and explore the transferability of data among different cities/countries. Moreover, policymakers can support the integration of NEE monitoring into international air quality frameworks (e.g., WHO, UNECE).
- Euro 7 is the first regulation worldwide that sets limits for brake and tyre wear emissions. However, the regulation sets only the PM (and PN in the future) limits, not the technology to achieve them. This may lead to penetration of technologies which can reduce PM brake and tyre emissions, but at the same time, increase toxicity. Regulations such as EU's REACH regulation which already addresses the risks posed by hazardous chemicals, including those used in tyre production, could serve as a foundation for developing future complementary regulations to address the trade-offs between wear and toxicity over component/vehicle lifetime to evaluate long-term environmental impacts [123].

- Promoting the need for new, definitive conclusions on measures like wear-resistant components and materials (e.g., brake pads, low-density vehicle materials, tyre formulations etc.), road run-off treating, and particle collection/ filtration devices is essential.
- Securing sufficient funding for research and development, as well as supporting on-road measurements is also very important to close the knowledge gaps on NEEs and their effectiveness of potential measures. Policymakers can push for global funding mechanisms to support innovation and advocate for global industry cooperation in designing and testing next-generation tyres and brake components with reduced wear and toxicity. Policymakers may support international partnerships for large-scale studies on NEE health and environmental effects as well as fostering industry-academia collaboration to accelerate innovation and policy adaptation.

In conclusion, addressing NEEs is vital to achieving sustainable urban air quality improvements and protecting public health. It is important for policymakers to realise that Euro 7 alone is not a standalone solution, but a starting point that requires further actions in order to achieve meaningful environmental solutions in a timely manner. Targeted interventions, supported by robust policies, innovation, and international collaboration, can pave the way for a cleaner and healthier future. Intervention strategies should be regularly evaluated and refined as new data and technologies emerge to ensure alignment with air quality targets and public health goals.

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References

[1] D. Dajnak, D. Evangelopoulos, N. Kitwiroon, S. Beevers, and H. Walton, 'London Health Burden of Current Air Pollution and Future Health Benefits of Mayoral Air Quality Policies', Environmental Research GroupImperial College London, 2021.

[2] *WHO Global Air Quality Guidelines: Particulate Matter (PM2. 5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*, 1st ed. Geneva: World Health Organization, 2021.

[3] I. Manisalidis, E. Stavropoulou, A. Stavropoulos, and E. Bezirtzoglou, 'Environmental and Health Impacts of Air Pollution: A Review', *Front. Public Health*, vol. 8, Feb. 2020, doi: 10.3389/fpubh.2020.00014.

[4] European Commission, *Handbook on the external costs of transport*. 2019. doi: 10.2832/27212.

[5] D. Birchby, J. Sendall, and J. Stedman, 'Air Quality damage cost update 2023FINAL Report', Ricardo Energy & Environment, Sep. 2023. [Online]. Available: https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2301090900_Damage_cost_update_2023_Final.pdf

[6] *WHO Global Air Quality Guidelines*, 2021. [Online]. Available: https://www.who.int/news-room/questions-and-answers/item/who-global-air-quality-guidelines

[7] *Directive of the European Parliament and of the Council on ambient air quality and cleaner air for Europe.*, 2022/0347(COD), 2024. [Online]. Available: https://data.consilium.europa.eu/doc/document/PE-88-2024-INIT/en/pdf

[8] GLA and TfL Air Quality, 'London Atmospheric Emisions Inventory (LAEI) 2019'. [Online]. Available: https://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory--laei--2019

[9] 'Air Quality in London 2016-2024', Greater London Authority, Mar. 2024. [Online]. Available: https://www.london.gov.uk/media/105046/download

[10] T. Smith, 'The Environmental Act 2021what to expect in 2022', LEXOLOGY. [Online]. Available: https://www.lexology.com/library/detail.aspx?g=9570b198-61a2-4bbf-b7f5-7da3c6fc7dba#:~:text=The%20Environment%20Act%20gives%20the%20Secretary%20of%20State,a%20variety%20of%20areas%20relating%20to%20the%20environment.

[11] J. Mitchell *et al.*, 'Air Pollutant Inventories for England, Scotland, Wales and Northern Ireland: 2005-2022National Atmospheric Emissions Inventory'. National Atmospheric Emissions Inventory, 2024. [Online]. Available: https://naei.energysecurity.gov.uk/reports/air-pollutant-inventories-england-scotland-wales-and-northern-ireland-2005-2022

[12] 'Officially reported emission dataEMEP Centre on Emission Inventories and Projections'. EMEP Centre on Emission Inventories and Projections. [Online]. Available: https://www.ceip.at/webdab-emission-database/reported-emissiondata

[13] B. Giechaskiel *et al.*, 'Contribution of Road Vehicle Tyre Wear to Microplastics and Ambient Air Pollution', *Sustainability*, vol. 16, no. 2, p. 522, Jan. 2024, doi: 10.3390/su16020522.

[14] 'European Envrionment Agency (EEA)An official website of the European Union'. [Online]. Available: https://www.eea.europa.eu/en

[15] 'European Environment Agency (EEA)European City Air Quality Viewer'. [Online]. Available: https://www.eea.europa.eu/en/topics/in-depth/air-pollution/european-city-air-quality-viewer

[16] 'European Environment AgencyEuropean Environment and Health Atlas'. [Online]. Available: https://discomap.eea.europa.eu/atlas/

[17] 'Barcelona's Local Pollution Model 2021Barcelona City Council'. [Online]. Available: https://ajuntament.barcelona.cat/qualitataire/sites/default/files/qa_balanscontaminaciolocal2021.pdf

[18] 'European Union Urban Access RegulationsBarcelona'. [Online]. Available: https://urbanaccessregulations.eu/countries-mainmenu-147/spain/barcelona

[19] 'European Union Urban Access RegulationsMilan'.

[20] 'Italian Emission Inventory (INEMAR)'. [Online]. Available: https://www.inemar.eu/xwiki/bin/view/InemarWiki/Emission+Inventory

[21] 'Lombardy's Regional Agency for Environmental Protection (ARPA Lombardia)'. [Online]. Available: https://www.arpalombardia.it/

[22] 'INEMAR ARPA Lombardia Emissions Inventory 2021'. [Online]. Available: https://app.powerbi.com/view?r=eyJrIjoiMDhkNDNkYmEtMDlhOS00NjIyLTkyNjgtZTY4MjdlNTRhYzg1IiwidCI6ImU5MmRiZTAwLTQ0OTItNGIxOC05YTQ4LM5MmEyN2M2YmQ2NSIsImMiOjh9

[23] 'ARPA Lombardy Regional Emission Inventory 2021'. [Online]. Available: https://www.arpalombardia.it/media/dgxikma5/report_inventario_2021.pdf

[24] European Commission. Directorate General for Internal Market, Industry, Entrepreneurship and SMEs., *Euro 7 impact assessment study.* LU: Publications Office, 2022. Accessed: Mar. 24, 2025. [Online]. Available: https://data.europa.eu/doi/10.2873/249061

[25] 'COPERTEmisia: The industry standard emissions calculator'. [Online]. Available: https://copert.emisia.com/

[26] 'National Atmospheric Emissions InventoryDevolved Administration Air Pollutants Inventory'. [Online]. Available: https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fnaei.energysecurity.gov.uk%2Fsites%2Fdefault%2Ffiles%2F2024-10%2FDA_air_pollutant_inventory_2005-2022.xlsb&wdOrigin=BROWSELINK

[27] T. Karageorgiou, Z. Samaras, L. Ntziachristos, B. Giechaskiel, T. Grigoratos, and P. Dilara, 'Impacts of Light-Duty Vehicles' Brake Emissions in Europe', in *EuroBrakes Conference*, EMISIA SA, Aristotle University of Thessaloniki, JRC & DG ENV, 2024. doi: 10.46720/eb2024-efa-017.

[28] B. Giechaskiel, T. Grigoratos, P. Dilara, T. Karageorgiou, L. Ntziachristos, and Z. Samaras, 'Light-Duty Vehicle Brake Emission Factors', *Atmosphere*, vol. 15, no. 1, p. 97, Jan. 2024, doi: 10.3390/atmos15010097.

[29] T. Karageorgiou, M. Perdikopoulos, G. Paisiou, W. Verhoeve, and G. Mellios, 'Research of the non-tailpipe emissions from road traffic as a result of the wear and tear of brakes, tyres and road surfaces for Flemish policy Call for Tender No: By invitation Report Title Non-exhaust PM emissions Review', EMISIA SA, 2023.

[30] 'PMP 54th session, UNECE Particle Measurement Programme PMP', Geneva, Sep. 2024. [Online]. Available: https://wiki.unece.org/display/trans/PMP+54th+session+-+Geneva+09.01.2024

[31] '1.A.3.b.i-iv Road transport 2024 — European Environment Agency Guidebook'. [Online]. Available: https://www.eea.europa.eu/publications/emep-eea-guidebook-2023/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view

[32] 'Emission Factors for Transport 2024National Atmospheric Emissions Inventory (NAEI)'. [Online]. Available: https://naei.energysecurity.gov.uk/emission-factors/emission-factors-transport

[33] I. Goßmann, R. Süßmuth, and B. M. Scholz-Böttcher, 'Plastic in the air?!Spider webs as spatial and temporal mirror for microplastics including tire wear particles in urban air', *Sci. Total Environ.*, vol. 832, p. 155008, Aug. 2022, doi: 10.1016/j.scitotenv.2022.155008.

[34] H. Kang, S. Park, B. Lee, I. Kim, and S. Kim, 'Concentration of Microplastics in Road Dust as a Function of the Drying Period—A Case Study in G City, Korea', *Sustainability*, vol. 14, no. 5, p. 3006, Mar. 2022, doi: 10.3390/su14053006.

[35] D. Venghaus, J. W. Neupert, and M. Barjenbruch, 'Tire Wear Monitoring Approach for Hotspot Identification in Road Deposited Sediments from a Metropolitan City in Germany', *Sustainability*, vol. 15, no. 15, p. 12029, Aug. 2023, doi: 10.3390/su151512029.

[36] M. Huber, L. Schubert, D. Heuberger, and P. Fischer, 'Assessing Tire Abrasion and Airborne Tire Emissions on an Enclosed Drum Dynamometera Euro 7 Approach', in *EuroBrake Conference*, 2024.

[37] M. Jekel, ‘Scientific Report on Tyre and Road Wear Particles, TRWP, in the aquatic environment’, European Tyre & Rubber Manufacturers Association (ETRMA), 2019.

[38] S. Schläfle, H.-J. Unrau, and F. Gauterin, ‘Influence of Load Condition, Tire Type, and Ambient Temperature on the Emission of Tire–Road Particulate Matter’, *Atmosphere*, vol. 14, no. 7, p. 1095, Jun. 2023, doi: 10.3390/atmos14071095.

[39] D. Silvestro, ‘ADAC Tyre test’, Apr. 28, 2022. [Online]. Available: file:///C:/Users/VelliadouDanai(emisi/Downloads/TA-02-02%20Study_ADAC_tyre_abrasion_110522_en-GB%20(1).pdf

[40] B. Giechaskiel, T. Grigoratos, P. Dilara, and V. Franco, ‘Environmental and Health Benefits of Reducing Tyre Wear Emissions in Preparation for the New Euro 7 Standard’, *Sustainability*, vol. 16, no. 24, p. 10919, Dec. 2024, doi: 10.3390/su162410919.

[41] C. Johansson, ‘Effectiveness of air quality measures in Stockholm’. Stockholm University & Environment and Health Administration Stockholm, Jan. 13, 2016.

[42] D. C. S. Beddows and R. M. Harrison, ‘PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles’, *Atmos. Environ.*, vol. 244, p. 117886, Jan. 2021, doi: 10.1016/j.atmosenv.2020.117886.

[43] V. R. J. H. Timmers and P. A. J. Achten, ‘Non-exhaust PM emissions from electric vehicles’, *Atmos. Environ.*, vol. 134, pp. 10–17, Jun. 2016, doi: 10.1016/j.atmosenv.2016.03.017.

[44] B. Giechaskiel *et al.*, ‘Tyre Wear under Urban, Rural, and Motorway Driving Conditions at Two Locations in Spain and China’, *Lubricants*, vol. 12, no. 10, p. 338, Sep. 2024, doi: 10.3390/lubricants12100338.

[45] Y. Umidbek, ‘Influence of Ambient Temperature on the Intensity of Tread Wear of Large Tires’, vol. 13, pp. 100–105, Dec. 2022.

[46] A. Beji *et al.*, ‘Non-exhaust particle emissions under various driving conditions: Implications for sustainable mobility’, *Transp. Res. Part Transp. Environ.*, vol. 81, Apr. 2020, doi: 10.1016/j.trd.2020.102290.

[47] S. Saladin, A. Boies, and C. Giorio, ‘Airborne Tire Wear Particles: A Critical Reanalysis of the Literature Reveals Emission Factors Lower than Expected’, *Environ. Sci. Technol. Lett.*, vol. 11, no. 12, pp. 1296–1307, Dec. 2024, doi: 10.1021/acs.estlett.4c00792.

[48] N. Molden, ‘Emissions AnalyticsHow to reduce emissions of micro particles from tyres to minimise health and environmental impact and avoid reputational damage’, presented at the Automotive Tire Technology 2023, Jan. 24, 2023. [Online]. Available: https://static1.squarespace.com/static/5a9400b37e3c3a8c47522029/t/64fb3d1f4219e47dc76a9e75/1694186786410/Emissions+Analytics+Automotive+Tire+Technology+January+2023+v2.pdf

[49] F. Biesse and P. Schaal, ‘Refined characterization of Tire Road Wear Particles emissions’, presented at the Tire Technology Conference 2025, Feb. 2025.

[50] M. Penkała, P. Ogrodnik, and W. Rogula-Kozłowska, ‘Particulate matter from the road surface abrasion as a problem of non-exhaust emission control’, *Environ.MDPI*, vol. 5, no. 1, pp. 1–13, Jan. 2018, doi: 10.3390/environments5010009.

[51] M. A. Costagliola *et al.*, ‘Non-Exhaust Particulate Emissions from Road Transport Vehicles’, *Energies*, vol. 17, no. 16, Aug. 2024, doi: 10.3390/en17164079.

[52] B. Baensch-Baltruschat, B. Kocher, F. Stock, and G. Reifferscheid, ‘Tyre and road wear particles (TRWP)A review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment’, *Sci. Total Environ.*, vol. 733, Sep. 2020, doi: 10.1016/j.scitotenv.2020.137823.

[53] V. Forest and J. Pourchez, ‘Biological effects of brake wear particles in mammalian models: A systematic review’, *Sci. Total Environ.*, vol. 905, p. 167266, Dec. 2023, doi: 10.1016/j.scitotenv.2023.167266.

[54] G. Melzi *et al.*, ‘Toxicological Profile of PM from Different Sources in the Bronchial Epithelial Cell Line BEAS-2B’, *Toxics*, vol. 11, no. 5, p. 413, Apr. 2023, doi: 10.3390/toxics11050413.

[55] H. Barosova *et al.*, ‘Biological response of an in vitro human 3D lung cell model exposed to brake wear debris varies based on brake pad formulation’, *Arch. Toxicol.*, vol. 92, no. 7, pp. 2339–2351, Jul. 2018, doi: 10.1007/s00204-018-2218-8.

[56] M. Gasser *et al.*, ‘Toxic effects of brake wear particles on epithelial lung cells in vitro’, *Part. Fibre Toxicol.*, vol. 6, no. 1, p. 30, Dec. 2009, doi: 10.1186/1743-8977-6-30.

[57] J. Zhao, N. Lewinski, and M. Riediker, ‘Physico-Chemical Characterization and Oxidative Reactivity Evaluation of Aged Brake Wear Particles’, *Aerosol Sci. Technol.*, vol. 49, no. 2, pp. 65–74, Feb. 2015, doi: 10.1080/02786826.2014.998363.

[58] J. G. H. Parkin *et al.*, ‘Copper-enriched automotive brake wear particles perturb human alveolar cellular homeostasis’, *Part. Fibre Toxicol.*, vol. 22, no. 1, p. 4, Feb. 2025, doi: 10.1186/s12989-024-00617-2.

[59] M. E. Gerlofs-Nijland *et al.*, ‘Inhalation toxicity profiles of particulate matter: a comparison between brake wear with other sources of emission’, *Inhal. Toxicol.*, vol. 31, no. 3, pp. 89–98, Feb. 2019, doi: 10.1080/08958378.2019.1606365.

[60] S. S. Shetty *et al.*, ‘Environmental pollutants and their effects on human health’, *Heliyon*, vol. 9, no. 9, Sep. 2023, doi: 10.1016/j.heliyon.2023.e19496.

[61] J. C. Fussell *et al.*, ‘A Review of Road Traffic-Derived Non-Exhaust Particles: Emissions, Physicochemical Characteristics, Health Risks, and Mitigation Measures’, *Environ. Sci. Technol.*, vol. 56, no. 11, pp. 6813–6835, Jun. 2022, doi: 10.1021/acs.est.2c01072.

[62] K.-H. Kim, E. Kabir, and S. Kabir, ‘A review on the human health impact of airborne particulate matter’, *Environ. Int.*, vol. 74, pp. 136–143, Jan. 2015, doi: 10.1016/j.envint.2014.10.005.

[63] U.S. Environmental Protection Agency, Office of Research and Development, ‘Black Carbon Research and Future StrategiesReducing emissions, improving human health and taking action on climate change.’, Oct. 2011, [Online]. Available: https://www.epa.gov/sites/default/files/2013-12/documents/black-carbon-fact-sheet_0.pdf

[64] Y. Lyu and U. Olofsson, ‘On black carbon emission from automotive disc brakes’, *J. Aerosol Sci.*, vol. 148, p. 105610, Oct. 2020, doi: 10.1016/j.jaerosci.2020.105610.

[65] A. Martins *et al.*, ‘Tackling Black Carbon: How to unlock fast climate and clean air benefits.’, London: Clean Air Fund, 2025.

[66] United States Environmental Protection Agency, ‘Health and Environmental Effects of Particulate Matter (PM)’. [Online]. Available: https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm

[67] J. Kukutschová *et al.*, ‘Wear mechanism in automotive brake materials, wear debris and its potential environmental impact’, *Wear*, vol. 267, no. 5–8, pp. 807–817, Jun. 2009, doi: 10.1016/j.wear.2009.01.034.

[68] T. Grigoratos and G. Martini, ‘Brake wear particle emissions: a review’, *Environ. Sci. Pollut. Res.*, vol. 22, pp. 2491–2504, 2015, doi: https://doi.org/10.1007/s11356-014-3696-8.

[69] R. Ciudin, P. C. Verma, S. Gialanella, and G. Straffelini, ‘Wear debris materials from brake systems: environmental and health issues’, presented at the SUSTAINABLE CITY 2014, Siena, Italy, Sep. 2014, pp. 1423–1434. doi: 10.2495/SC141202.

[70] M. E. Gerlofs-Nijland *et al.*, ‘Inhalation toxicity profiles of particulate matter: a comparison between brake wear with other sources of emission’, *Inhal. Toxicol.*, vol. 31, no. 3, pp. 89–98, Feb. 2019, doi: 10.1080/08958378.2019.1606365.

[71] F. Sommer *et al.*, ‘Tire abrasion as a major source of microplastics in the environment’, *Aerosol Air Qual. Res.*, vol. 18, no. 8, pp. 2014–2028, Aug. 2018, doi: 10.4209/aaqr.2018.03.0099.

[72] S. Wagner, T. Hüffer, P. Klöckner, M. Wehrhahn, T. Hofmann, and T. Reemtsma, ‘Tire wear particles in the aquatic environmentA review on generation, analysis, occurrence, fate and effects’, *Water Res.*, vol. 139, pp. 83–100, Aug. 2018, doi: 10.1016/j.watres.2018.03.051.

[73] S. Wagner, C. W. Funk, K. Müller, and D. J. Raithel, ‘The chemical composition and sources of road dust, and of tire and road wear particles–A review’, *Sci. Total Environ.*, vol. 926, May 2024, doi: 10.1016/j.scitotenv.2024.171694.

[74] ‘UNECE World Forum for Harmonization of Vehicle Regulations (WP.29)’. [Online]. Available: https://unece.org/wp29-introduction

[75] *Regulation on type-approval of motor vehicles and engines and of systems, components and separate technical units intended for such vehicles, with respect to their emissions and battery durability (Euro 7)Analysis of the final compromise text with a view to agreement.*, Interinstitutional File: 2022/0365(COD), Dec. 21, 2023. [Online]. Available: https://data.consilium.europa.eu/doc/document/ST-16960-2023-REV-1/en/pdf

[76] M. Dagan, 'Task Force on Tyre Abrasion (TF TA)', UNECE Working Party on Noise and Tyres (GRBP) (Former GRB). [Online]. Available: https://wiki.unece.org/pages/viewpage.action?pageId=160694352

[77] *Regulation (EU) 2024/1257 of the European Parliament and of the Council of 24 April 2024 on type-approval of motor vehicles and engines and of systems, components and separate technical units intended for such vehicles, with respect to their emissions and battery durability (Euro 7).*, 2024. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401257

[78] European Council, '"Fit for 55": Council adopts regulation on CO2 emissions for new cars and vans.', Council of the EU Press Releases. [Online]. Available: https://www.consilium.europa.eu/en/press/press-releases/2023/03/28/fit-for-55-council-adopts-regulation-on-co2-emissions-for-new-cars-and-vans/

[79] *Commission Directive 98/12/EC of 27 January 1998 adapting to technical progress Council Directive 71/320/EEC on the approximation of the laws of the Member States relating to the braking devices of certain categories of motor vehicles and their trailers (Text with EEA relevance)*, Jan. 27, 1998. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A31998L0012

[80] *DIRECTIVE 2000/53/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 September 2000 on end-of life vehicles.* [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0053-20130611&qid=1405610569066&from=EN

[81] *Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air.* [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1486475021303&uri=CELEX:02004L0107-20150918

[82] *Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe.* [Online]. Available: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32008L0050

[83] *Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC (Text with EEA relevance).* [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.344.01.0001.01.ENG&toc=OJ:L:2016:344:TOC

[84] European Commission, ‘Zero Pollution Action PlanTowards zero pollution for air, water and soil.’, Energy, Climate change, Environment.

[85] M. Elmgren and K. Eneroth, ‘Acting on non-exhaust traffic sources to reduce PM’. SLB-analys, Oct. 08, 2021. doi: https://fairmode.jrc.ec.europa.eu/document/fairmode/event/presentation/Brussels-technical-2021/p2_ct5_non_exhaustPM_stockholm_8oct2021.pdf.

[86] Transport for London, ‘Healthy Streets’. [Online]. Available: https://tfl.gov.uk/corporate/about-tfl/how-we-work/planning-for-the-future/healthy-streets

[87] ‘Policy Paper: Clean Air Strategy UK 2019’. [Online]. Available: https://www.gov.uk/government/publications/clean-air-strategy-2019

[88] Z. Azdad, B. Stoll, and J. Muller, ‘The development trends of low- and zero-emission zones in Europe’, Clean Cities Campaign, Transport & Environment. [Online]. Available: https://cleancitiescampaign.org/wp-content/uploads/2022/07/The-development-trends-of-low-emission-and-zero-emission-zones-in-Europe-1.pdf

[89] European Union, ‘Urban Access Regulations Map’. [Online]. Available: https://urbanaccessregulations.eu/userhome/map

[90] ‘London-wide Ultra Low Emission Zone One Year Report’. [Online]. Available: https://www.london.gov.uk/programmes-strategies/environment-and-climate-change/environment-and-climate-change-publications/london-wide-ultra-low-emission-zone-one-year-report?check_logged_in=1

[91] ‘The evolution of Low Emission Zones (LEZ) in Europe: Impacts and perspectives’, ARVAL BNP PARIBAS GROUP. [Online]. Available: https://www.arval.com/amo/the-evolution-of-low-emission-zones-lez-in-europe-impacts-and-perspectives-amo#:~:text=Low%20emission%20zones%20%28LEZs%29%20face%20various%20challenges%20and,more%20polluting%20vehicles%2C%20exacerbating%20inequalities.%20...%20More%20items

[92] K. Vanherle, S. Lopez-Aparicio, H. Grythe, A. Lukewille, A. Unterstaller, and I. Mayeres, ‘ETC/ATNI Report 5/2020: Transport Non-exhaust PM-emissions. An overview of emission estimates, relevance, trends and policies’. [Online]. Available: https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-5-2020-transport-non-exhaust-pm-emissions-an-overview-of-emission-estimates-relevance-trends-and-policies

[93] ‘Targets in the Mayor’s Transport Strategy’, London Assembly. [Online]. Available: https://www.london.gov.uk/who-we-are/what-london-assembly-does/questions-mayor/find-an-answer/targets-mayors-transport-strategy

[94] tomtom, ‘London Traffic Index’. [Online]. Available: https://www.tomtom.com/traffic-index/london-traffic/

[95] BOSCH, 'Bosch and PTV Group: Alliance for better air'. [Online]. Available: https://www.bosch-presse.de/pressportal/de/en/bosch-and-ptv-group-alliance-for-better-air-226240.html

[96] OECD, *Non-exhaust Particulate Emissions from Road Transport*. OECD, 2020. doi: 10.1787/4a4dc6ca-en.

[97] S. K. Fondzenyuy *et al.*, 'The Impact of Speed Limit Change on Emissions: A Systematic Review of Literature', *Sustainability*, vol. 16, no. 17, p. 7712, Sep. 2024, doi: 10.3390/su16177712.

[98] J. Casanova and N. Fonseca, 'Envrionmental Assessment of Low Speed Policies for Motor Vehicle Mobility in City Centres', *Glob. NEST*, vol. 14, no. 2, pp. 192–201, 2012.

[99] I. Gehrke, S. Schläfle, R. Bertling, M. Öz, and K. Gregory, 'Review: Mitigation measures to reduce tire and road wear particles', *Sci. Total Environ.*, vol. 904, p. 166537, Dec. 2023, doi: 10.1016/j.scitotenv.2023.166537.

[100] H. A. Rakha, M. Farag, and H. Foroutan, 'Electric versus gasoline vehicle particulate matter and greenhouse gas emissions: Large-scale analysis', *Transp. Res. Part Transp. Environ.*, vol. 140, p. 104622, Mar. 2025, doi: 10.1016/j.trd.2025.104622.

[101] 'Noise control service', Barcelona City CouncilUrban Planning, Ecological Transition, Urban Services and Housing. [Online]. Available: https://ajuntament.barcelona.cat/ecologiaurbana/en/services/the-city-works/maintenance-of-public-areas/energy-management/noise-control-service?utm_source=chatgpt.com

[102] 'New measures for reducing noise pollution', Barcelona City CouncilUrban Planning, Ecological Transition, Urban Services and Housing. [Online]. Available: https://ajuntament.barcelona.cat/ecologiaurbana/en/noticia/new-measures-for-reducing-noise-pollution_1171824

[103] K. T. Gradin and A. H. Åström, 'Comparative life cycle assessment of car disc brake systems—case study results and method discussion about comparative LCAs', *Int. J. Life Cycle Assess.*, vol. 25, no. 2, pp. 350–362, Feb. 2020, doi: 10.1007/s11367-019-01704-9.

[104] I. Bianchi, A. Forcellese, M. Simoncini, A. Vita, L. Delledonne, and V. Castorani, 'Life cycle assessment of carbon ceramic matrix composite brake discs containing reclaimed prepreg scraps', *J. Clean. Prod.*, vol. 413, p. 137537, Aug. 2023, doi: 10.1016/j.jclepro.2023.137537.

[105] Verified, 'How Often Should You Have Your Brake Pads Changed?' [Online]. Available: https://www.verified.org/articles/guides/how-often-to-change-brake-pads?utm_source=chatgpt.com

[106] J. Araujo-Morera, M. Hernández Santana, R. Verdejo, and M. A. López-Manchado, 'Giving a Second Opportunity to Tire Waste: An Alternative Path for the Development of Sustainable Self-Healing Styrene–Butadiene Rubber Compounds Overcoming the Magic Triangle of Tires', *Polymers*, vol. 11, no. 12, p. 2122, Dec. 2019, doi: 10.3390/polym11122122.

[107] M. Ayar, A. Dalkiran, U. Kale, A. Nagy, and T. H. Karakoc, 'Investigation of the Substitutability of Rubber Compounds with Environmentally Friendly Materials', *Sustainability*, vol. 13, no. 9, p. 5251, May 2021, doi: 10.3390/su13095251.

[108] G. Papaioannou, J. Jerrelind, and L. Drugge, 'Multi-Objective Optimisation of Tyre and Suspension Parameters during Cornering for Different Road Roughness Profiles', *Appl. Sci.*, vol. 11, no. 13, p. 5934, Jun. 2021, doi: 10.3390/app11135934.

[109] M. Li, K. Wang, and Y. Xiong, 'Multiple Intermolecular Interaction to Improve the Abrasion Resistance and Wet Skid Resistance of Eucommia Ulmoides Gum/Styrene Butadiene Rubber Composite', *Materials*, vol. 14, no. 18, p. 5246, Sep. 2021, doi: 10.3390/ma14185246.

[110] A. Piscitello, C. Bianco, A. Casasso, and R. Sethi, 'Non-exhaust traffic emissions: Sources, characterization, and mitigation measures', *Sci. Total Environ.*, p. 144440, 2021, doi: https://doi.org/10.1016/j.scitotenv.2020.144440.

[111] Transport for London, 'Bus safety strategy'. [Online]. Available: https://content.tfl.gov.uk/bus-safety-strategy.pdf

[112] Tallano Technologies, 'TAMIC technology to reduce particulate matter emissions'. [Online]. Available: https://www.tallano-technologies.com/en/tamic-solution/

[113] J. Wilson, 'World's first device to capture harmful tyre particles invented by students', Imperial College London. [Online]. Available: https://www.imperial.ac.uk/news/195595/worlds-first-device-capture-harmful-tyre/

[114] Mann+Hummel, 'Brake dust particle filter', OEM Products, Fine dust filters. [Online]. Available: https://oem.mann-hummel.com/en/oem-products/fine-dust-filters/brake-dust-particle-filter.html#:~:text=The%20passive%20brake%20dust%20particle%20filter%20from%20MANN%2BHUMMEL,be%20adapted%20to%20different%20brake%20sizes%20and%20concepts.

[115] MBM Science Bridge, 'Efficient reduction of brake dust by filter sealing and housing design'. [Online]. Available: https://sciencebridge.de/en/efficient-reduction-and-filtering-of-brake-dust.html

[116] The Brake Report, 'Chassis Brakes and MANN+HUMMEL Work To Cut Particulate Emissions', Automotive. [Online]. Available: https://thebrakereport.com/chassis-brakes-mannhummel-cut-particulate-emissions/?utm_source=chatgpt.com

[117] AIRUSE, 'Testing and development of air quality mitigation measures in Southern Europe', Layman's Report LIFE11/ENV/ES/58, 2016. [Online]. Available: https://airuse.eu/wp-content/uploads/2015/06/2016_AIRUSE-D5a-Laymans-report_-EN.pdf

[118] I. Gehrke *et al.*, 'Study on TRWP Mitigation (State of KnowledgeSOK) | TRWP-X', Fraunhofer UMSICHT, Carnegie Mellon University, KIT, ETRMA, U.S. Tire Manufacturers, 2023.

[119] 'EmisiaSibyl Baseline COPERT', Vehicle fleet, activity, emissions and energy consumption projections for the EU 27 member states (plus 10 additional countries*). [Online]. Available: https://copert.emisia.com/sibyl-baseline/

[120] Transport for London, 'Mayor's Transport Strategy: Supporting Evidence Outcomes Summary Report', Jul. 2017. [Online]. Available: https://content.tfl.gov.uk/mts-outcomes-summary-report.pdf

[121] JATO, 'European new car market growth in 2024 driven by hybrids and Chinese brands'. [Online]. Available: https://www.jato.com/resources/media-and-press-releases/european-new-car-market-growth-in-2024-driven-by-hybrids-and-chinese-brands#:~:text=SUVs%20remained%20the%20best%2Dselling,%2C%20up%20 4%25%20from%202023.

[122] EU Urban Mobility Observatory, 'Paris introduces triple parking fees for SUVs', News Article. [Online]. Available: https://urban-mobility-observatory.transport.ec.europa.eu/news-events/news/paris-introduces-triple-parking-fees-suvs-2024-02-12_en?utm_source=chatgpt.com

[123] D. Navarro, D. Samaraweera, P. Srivastava, and J. Kirby, 'Exploring global influences on the tyre industry: Chemicals of concern, microplastics and design LITERATURE REVIEW', Commonwealth Scientific and Industrial Research Organisation (CSIRO), Nov. 2024. [Online]. Available: https://www.tyrestewardship.org.au/wp-content/uploads /2024/11/CSIRO-TSA-Global-Review-Report-2024.pdf?utm_source=chatgpt.com

[124] I. Cunha-Lopes *et al.*, 'Cunha-Lopes_2022', *Atmos. Environ.*, vol. 286, p. 119221, 2022, doi: https://doi.org/10.1016/j.atmosenv.2022.119221.

[125] I. Kaddoura, R. Ewert, and K. Martins-Turner, 'Exhaust and non-exhaust emissions from today's and future road transport: A simulation-based quantification for Berlin', *Transp. Res. Procedia*, vol. 62, pp. 696–702, 2022, doi: https://doi.org/10.1016/j.trpro.2022.02.086.

[126] F. Amato *et al.*, 'Traffic induced particle resuspension in Paris: Emission factors and source contributions', *Atmos. Environ.*, vol. 129, pp. 114–124, Mar. 2016, doi: 10.1016/j.atmosenv.2016.01.022.

[127] H. Jang, 'Brake Friction Materials', *Encyclopedia of Tribology*. Springer US, pp. 263–273, 2013. doi: 10.1007/978-0-387-92897-5.

[128] W. Österle, H. Kloß, I. Urban, and A. I. Dimitriev, 'Towards a better understanding of brake friction materials', *Wear*, vol. 263, no. 7–12, pp. 1189–1201, 2007.

[129] H. Hagino, 'Feasibility of Measuring Brake-Wear Particle Emissions from a Regenerative-Friction Brake Coordination System via Dynamometer Testing', *Atmosphere*, vol. 15, p. 75, 2024, doi: https://doi.org/10.3390/atmos15010075.

[130] Q. Zhang *et al.*, 'Direct measurement of brake and tire wear particles based on real-world driving conditions', *Sci. Total Environ.*, vol. 906, p. 167764, Jan. 2024, doi: 10.1016/j.scitotenv.2023.167764.

[131] T. Feißel and D. Carl, 'Evaluation of influence variables and error sources of the UN-GTR24 brake emission measurement procedure', in *EuroBrake Conference*, 2024. Accessed: Oct. 15, 2024. [Online]. Available: https://www.fisita.org/library/eb2024-efa-008

[132] L. Adamczak, 'At source brake dust active filtering system', in *FISITA*, 2023. Accessed: Jan. 21, 2025. [Online]. Available: https://www.fisita.org/library/eb2023-efa-008

[133] H. Hagino, A. Iwata, and T. Okuda, 'Iron Oxide and Hydroxide Speciation in Emissions of Brake Wear Particles from Different Friction Materials Using an X-ray Absorption Fine Structure', *Atmosphere*, vol. 15, no. 1, p. 49, Dec. 2023, doi: 10.3390/atmos15010049.

[134] M. P. Huber, J. Murg, G. Steiner, and Wanek-Rü, 'Assessing a vehicle's real-world brake wear particle emissions on public roads', in *EuroBrake Conference*, TU Graz & AVL List GmbH, 2023. doi: http://dx.doi.org/10.46720/eb2023-tst-002.

[135] A. Sin, 'Comparison of different tribological couples respect to PM10 emissions', in *EuroBrake Conference*, 2023. Accessed: Oct. 15, 2024. [Online]. Available: https://www.fisita.org/library/eb2023-efa-010

[136] L. Storch *et al.*, 'Comprehensive Analysis of Current Primary Measures to Mitigate Brake Wear Particle Emissions from Light-Duty Vehicles', *Atmosphere*, vol. 14, no. 4, p. 712, Apr. 2023, doi: 10.3390/atmos14040712.

[137] J. Andersson and M. Campbell, 'Measurement of Emissions from Brake and Tyre Wear', Final ReportPhase 1 Ref. T0018-TETI0037, Feb. 2023. [Online]. Available: https://assets.publishing.service.gov.uk/media/647ed40cb32b9e000ca9621d/measurement-of-emissions-brake-and-tyre-wear.pdf

[138] M. P. Huber, A. Mamakos, M. Hofbauer, P. Fishcer, A. Klug, and G. Steiner, 'Real driving emissions sampling system for brake wear particle measurement', in *EuroBrake Conference*, 2022. Accessed: Oct. 15, 2024. [Online]. Available: https://www.fisita.org/library/eb2022-ebs-010

[139] Y. Liu *et al.*, 'Brake wear induced PM10 emissions during the world harmonised light-duty vehicle test procedure-brake cycle', *J. Clean. Prod.*, vol. 361, p. 132278, Aug. 2022, doi: 10.1016/j.jclepro.2022.132278.

[140] S.-H. Woo, H. Jang, S.-B. Lee, and S. Lee, 'Comparison of total PM emissions emitted from electric and internal combustion engine vehicles: An experimental analysis', *Sci. Total Environ.*, vol. 842, p. 156961, Oct. 2022, doi: 10.1016/j.scitotenv.2022.156961.

[141] S.-H. Woo, H. Jang, M. Y. Na, H. J. Chang, and S. Lee, 'Characterization of brake particles emitted from non-asbestos organic and low-metallic brake pads under normal and harsh braking conditions', *Atmos. Environ.*, vol. 278, p. 119089, Jun. 2022, doi: 10.1016/j.atmosenv.2022.119089.

[142] D. Hesse, C. Hamatschek, K. Augsburg, T. Weigelt, A. Prahst, and S. Gramstat, 'Testing of Alternative Disc Brakes and Friction Materials Regarding Brake Wear Particle Emissions and Temperature Behavior', *Atmosphere*, vol. 12, no. 4, p. 436, Mar. 2021, doi: 10.3390/atmos12040436.

[143] S. H. Kim *et al.*, 'Dynamometric investigation on airborne particulate matter (Pm) from friction materials for automobile: Impact of abrasive and lubricant on pm emission factor', *Lubricants*, vol. 9, no. 12, p. 118, Dec. 2021, doi: 10.3390/lubricants9120118.

[144] J. Park *et al.*, 'Analysis of wear induced particle emissions from brake pads during the worldwide harmonized light vehicles test procedure (WLTP)', *Wear*, vol. 466–467, p. 203539, Feb. 2021, doi: 10.1016/j.wear.2020.203539.

[145] M. Vojtíšek-Lom *et al.*, 'Effects of braking conditions on nanoparticle emissions from passenger car friction brakes', vol. 788, p. 147779, 2021, doi: https://doi.org/10.1016/j.scitotenv.2021.147779.

[146] S.-H. Woo, Y. Kim, S. Lee, Y. Choi, and S. Lee, 'Characteristics of brake wear particle (BWP) emissions under various test driving cycles', *Wear*, vol. 480–481, p. 203936, Sep. 2021, doi: 10.1016/j.wear.2021.203936.

[147] C. Agudelo, R. T. Vedula, S. Collier, and A. Stanard, 'Brake Particulate Matter Emissions Measurements for Six Light-Duty Vehicles Using Inertia Dynamometer Testing', *SAE Int. J. Adv. Curr. Pract. Mobil.*, vol. 3, no. 2, pp. 994–1019, Oct. 2020, doi: 10.4271/2020-01-1637.

[148] S. Gramstat, T. Mertens, R. Waninger, and D. Lugovyy, 'Impacts on Brake Particle Emission Testing', *Atmosphere*, vol. 11, no. 10, p. 1132, Oct. 2020, doi: 10.3390/atmos11101132.

[149] S. H. Kim *et al.*, 'The Impact of Composition in Non-steel and Low-Steel Type Friction Materials on Airborne Brake Wear Particulate Emission', *Tribol. Lett.*, vol. 68, no. 4, p. 118, Dec. 2020, doi: https://doi.org/10.1007/s11249-020-01361-2.

[150] A. Mamakos, M. Arndt, D. Hesse, C. Hamatschek, and K. Augsburg, 'Comparison of Particulate Matter and Number Emissions from a Floating and a Fixed Caliper Brake System of the Same Lining Formulation', Oct. 2020. doi: 10.4271/2020-01-1633.

[151] F. H. Farwick zum Hagen *et al.*, 'On-road vehicle measurements of brake wear particle emissions', *Atmos. Environ.*, vol. 217, p. 116943, Nov. 2019, doi: 10.1016/j.atmosenv.2019.116943.

[152] H. Hagino, ‘Sensitivity and Reproducibility of Brake Wear Emission Measurements using JARI System’, in *50th PMP Meeting*, Japan Automobile Standards Internationalization Center (JASIC), 2019. Accessed: Oct. 15, 2024. [Online]. Available: https://www.bing.com/search?q=Sensitivity+and+Reproducibility+of+Brake+Wear+Particle+Emission+Measurements+Using+JARI+System&cvid=62c9d3da534346cbab49cddf19ae6081&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIICAEQ6QcY_FXSAQc2NjhqMGo0qAIAsAIB&FORM=ANAB01&PC=U531

[153] D. Hesse, K. Augsburg, and Feißel Toni, ‘Real Driving Emissions Measurement of Brake Dust Particles’, in *EB2019-FBR-017*, 2019. [Online]. Available: https://www.researchgate.net/publication/334671579

[154] A. Mamakos, M. Arndt, D. Hesse, and K. Augsburg, ‘Physical Characterization of Brake-Wear Particles in a PM10 Dilution Tunnel’, *Atmosphere*, vol. 10, no. 11, p. 639, Oct. 2019, doi: 10.3390/atmos10110639.

[155] M. Mathissen, T. Grigoratos, T. Lahde, and R. Vogt, ‘Brake wear particle emissions of a passenger car measured on a chassis dynamometer’, *Atmosphere*, vol. 10, no. 9, p. 556, Sep. 2019, doi: 10.3390/ATMOS10090556.

[156] Å. Sjödin, M. Ferm, A. Björk, and M. Rahmberg, ‘Wear particles from road traffic-a field, laboratory and modelling study. Final report’, 2010, doi: 10.13140/RG.2.2.18594.35524.

[157] N. Bukowiecki *et al.*, ‘PM10 emission factors for non-exhaust particles generated by road traffic in an urban street canyon and along a freeway in Switzerland’, *Atmos. Environ.*, vol. 44, no. 19, pp. 2330–2340, Jun. 2010, doi: 10.1016/j.atmosenv.2010.03.039.

[158] N. Bukowiecki *et al.*, ‘Real-World Emission Factors for Antimony and Other Brake Wear Related Trace Elements: Size-Segregated Values for Light and Heavy Duty Vehicles’, *Environ. Sci. Technol.*, vol. 43, no. 21, pp. 8072–8078, Nov. 2009, doi: 10.1021/es9006096.

[159] A. Iijima, K. Sato, K. Yano, M. Kato, K. Kozawa, and N. Furuta, ‘Emission Factor for Antimony in Brake Abrasion Dusts as One of the Major Atmospheric Antimony Sources’, *Environ. Sci. Technol.*, vol. 42, no. 8, pp. 2937–2942, Apr. 2008, doi: 10.1021/es702137g.

[160] A. Dahl *et al.*, ‘Traffic-generated emissions of ultrafine particles from pavement–tire interface’, *Atmos. Environ.*, vol. 40, no. 7, pp. 1314–1323, Mar. 2006, doi: 10.1016/j.atmosenv.2005.10.029.

[161] L. Luhana *et al.*, ‘Measurement of non-exhaust particulate matter’, European Commission Directorate General Transport and Environment, 2004.

[162] P. G. Sanders, N. Xu, T. M. Dalka, and M. M. Maricq, 'Airborne Brake Wear Debris: Size Distributions, Composition, and a Comparison of Dynamometer and Vehicle Tests', Environ. Sci. Technol., vol. 37, no. 18, pp. 4060–4069, Sep. 2003, doi: 10.1021/es034145s.

[163] B. D. Garg, S. H. Cadle, P. A. Mulawa, P. J. Groblicki, C. Laroo, and G. A. Parr, 'Brake Wear Particulate Matter Emissions', *Environ. Sci. Technol.*, vol. 34, no. 21, pp. 4463–4469, Nov. 2000, doi: 10.1021/es001108h.

[164] T. Charbouillot *et al.*, 'Methodology for the direct measurement of tire emission factors', *Sci. Total Environ.*, vol. 863, p. 160853, Mar. 2023, doi: 10.1016/j.scitotenv.2022.160853.

[165] T. Grigoratos, M. Gustafsson, O. Eriksson, and G. Martini, 'Experimental investigation of tread wear and particle emission from tyres with different treadwear marking', *Atmos. Environ.*, vol. 182, pp. 200–212, Jun. 2018, doi: 10.1016/j.atmosenv.2018.03.049.

[166] H. Yan, L. Zhang, L. Liu, and S. Wen, 'Investigation of the external conditions and material compositions affecting the formation mechanism and size distribution of tire wear particles', *Atmos. Environ.*, vol. 244, p. 118018, Jan. 2021, doi: 10.1016/j.atmosenv.2020.118018.

[167] Y. Tonegawa and S. Sasaki, 'Development of Tire-Wear Particle Emission Measurements for Passenger Vehicles', *Emiss. Control Sci. Technol.*, vol. 7, pp. 56–62, 2021, doi: https://doi.org/10.1007/s40825-020-00181-z.

[168] I. Park, H. Kim, and S. Lee, 'Characteristics of tire wear particles generated in a laboratory simulation of tire/road contact conditions', *J. Aerosol Sci.*, vol. 124, pp. 30–40, Oct. 2018, doi: 10.1016/j.jaerosci.2018.07.005.

[169] G. Kim and S. Lee, 'Characteristics of Tire Wear Particles Generated by a Tire Simulator under Various Driving Conditions', *Environ. Sci. Technol.*, vol. 52, no. 21, pp. 12153–12161, Nov. 2018, doi: 10.1021/acs.est.8b03459.

[170] C. A. Alves *et al.*, 'Physical and chemical properties of non-exhaust particles generated from wear between pavements and tyres', *Atmos. Environ.*, vol. 224, p. 117252, Mar. 2020, doi: 10.1016/j.atmosenv.2019.117252.

[171] M. Gustaffson *et al.*, 'NanoWear: nanoparticles from wear of tyres and pavements', Swedish National Road and Transport Research Institute (VTI), 2009. Accessed: Oct. 15, 2024. [Online]. Available: https://trid.trb.org/View/912843

[172] A. Stanard, T. DeFries, C. Palacios, and S. Kishan, 'Brake and Tire Wear Emissions', Eastern Research Group, Inc., 2021.

[173] J. M. Panko, J. Chu, M. L. Kreider, and K. M. Unice, 'Measurement of airborne concentrations of tire and road wear particles in urban and rural areas of France, Japan, and the United States', *Atmos. Environ.*, vol. 72, pp. 192–199, Jun. 2013, doi: 10.1016/j.atmosenv.2013.01.040.

[174] Emissions Analytics, ‘How tyre emissions hide in plain sight’, Newsletter.

[175] G. Geilenkirchen *et al.*, ‘Methods for calculating the emissions of transport in the Netherlands’, PBL Netherlands Environmental Assessment Agency, 2021.

[176] W. R. Pierson and W. W. Brachaczek, ‘Airborne Particulate Debris from Rubber Tires’, *Rubber Chem. Technol.*, vol. 47, no. 5, pp. 1275–1299, Nov. 1974, doi: 10.5254/1.3540499.

[177] K. J. Kupiainen, H. Tervahattu, M. Räisänen, T. Mäkelä, M. Aurela, and R. Hillamo, ‘Size and Composition of Airborne Particles from Pavement Wear, Tires, and Traction Sanding’, *Environ. Sci. Technol.*, vol. 39, no. 3, pp. 699–706, Feb. 2005, doi: 10.1021/es035419e.

[178] S. Khardi, ‘Emission Factors of Tyre Wear Particles Emitted by Light Road Vehicles in Real Driving Conditions: A New Challenge for Clean Road Transport to Improve Urban Air Quality’, *Atmosphere*, vol. 15, no. 6, p. 665, May 2024, doi: 10.3390/atmos15060665.

[179] Aatmeeyata, D. S. Kaul, and M. Sharma, ‘Traffic generated non-exhaust particulate emissions from concrete pavement: A mass and particle size study for two-wheelers and small cars’, *Atmos. Environ.*, vol. 43, no. 35, pp. 5691–5697, Nov. 2009, doi: 10.1016/j.atmosenv.2009.07.032.

[180] V. Jalali Farahani, A. Altuwayjiri, S. Taghvaee, and C. Sioutas, ‘Tailpipe and Nontailpipe Emission Factors and Source Contributions of PM_{10} on Major Freeways in the Los Angeles Basin’, *Environ. Sci. Technol.*, vol. 56, no. 11, pp. 7029–7039, Jun. 2022, doi: 10.1021/acs.est.1c06954.

[181] W. Hicks *et al.*, ‘Quantification of Non-Exhaust Particulate Matter Traffic Emissions and the Impact of COVID-19 Lockdown at London Marylebone Road’, *Atmosphere*, vol. 12, no. 2, p. 190, Jan. 2021, doi: 10.3390/atmos12020190.

[182] T. De Oliveira *et al.*, ‘Realistic assessment of tire and road wear particle emissions and their influencing factors on different types of roads’, *J. Hazard. Mater.*, vol. 465, p. 133301, 2024, doi: https://doi.org/10.1016/j.jhazmat.2023.133301.

[183] A. Rauterberg-Wulff, ‘The contribution of tyre and brake abrasion to soot levels in streets.’, Technische Univ. Berlin (Germany). Inst. fuer Technischen Umweltschutz, Germany, 1998.

[184] R. Gehrig *et al.*, ‘Mobile load simulators – A tool to distinguish between the emissions due to abrasion and resuspension of PM10 from road surfaces’, *Atmos. Environ.*, vol. 44, no. 38, pp. 4937–4943, Dec. 2010, doi: 10.1016/j.atmosenv.2010.08.020.

[185] S.-H. Woo, H. Jang, S.-H. Mun, Y. Lim, and S. Lee, ‘Effect of treadwear grade on the generation of tire PM emissions in laboratory and real-world driving conditions’, *Sci. Total Environ.*, vol. 838, p. 156548, Sep. 2022, doi: 10.1016/j.scitotenv.2022.156548.

[186] R. Gehrig *et al.*, 'Contribution of railway traffic to local PM10 concentrations in Switzerland', *Atmos. Environ.*, vol. 41, no. 5, pp. 923–933, Feb. 2007, doi: 10.1016/j.atmosenv.2006.09.021.

[187] J. Andersson, M. Campbell, I. Marshall, L. Kramer, and J. Norris, 'Measurement of Emissions from Brake and Tyre Wear', Final Report – Phase 1 Ref. T0018-TETI0037, Feb. 2023. [Online]. Available: https://assets.publishing.service.gov.uk/media/647ed40cb32b9e000ca9621d/measurement-of-emissions-brake-and-tyre-wear.pdf

[188] C. A. Alves, M. Soares, D. Figueiredo, and H. Oliveira, 'Effects of particle-bound polycyclic aromatic hydrocarbons and plasticisers from different traffic sources on the human alveolar epithelial cell line A549', *Atmos. Environ.*, vol. 303, p. 119736, Jun. 2023, doi: 10.1016/j.atmosenv.2023.119736.

[189] C. Puisney-Dakhli, E. K. Oikonomou, M. Tharaud, Y. Sivry, J.-F. Berret, and A. Baeza-Squiban, 'Effects of brake wear nanoparticles on the protection and repair functions of the airway epithelium', *Environ. Pollut.*, vol. 327, p. 121554, Jun. 2023, doi: 10.1016/j.envpol.2023.121554.

[190] M. Figliuzzi *et al.*, 'Copper-dependent biological effects of particulate matter produced by brake systems on lung alveolar cells', *Arch. Toxicol.*, vol. 94, no. 9, pp. 2965–2979, Sep. 2020, doi: 10.1007/s00204-020-02812-4.

[191] L. Selley *et al.*, 'Brake dust exposure exacerbates inflammation and transiently compromises phagocytosis in macrophages', *Metallomics*, vol. 12, no. 3, pp. 371–386, Mar. 2020, doi: 10.1039/c9mt00253g.

[192] C. Puisney *et al.*, 'Brake wear (nano)particle characterization and toxicity on airway epithelial cells *in vitro*', *Environ. Sci. Nano*, vol. 5, no. 4, pp. 1036–1044, 2018, doi: 10.1039/C7EN00825B.

[193] P. Peikertova *et al.*, 'Toxicity of the Airborne Brake Wear Debris', *SAE Int. J. Mater. Manuf.*, vol. 10, no. 1, pp. 2016-01–1914, Sep. 2016, doi: 10.4271/2016-01-1914.

[194] A. Kazimirova *et al.*, 'Automotive airborne brake wear debris nanoparticles and cytokinesis-block micronucleus assay in peripheral blood lymphocytes: A pilot study', *Environ. Res.*, vol. 148, pp. 443–449, Jul. 2016, doi: 10.1016/j.envres.2016.04.022.

[195] D. M. Bernstein *et al.*, 'Evaluation of the dose-response and fate in the lung and pleura of chrysotile-containing brake dust compared to TiO2, chrysotile, crocidolite or amosite asbestos in a 90-day quantitative inhalation toxicology study – Interim results Part 2: Histopathological examination, Confocal microscopy and collagen quantification of the lung and pleural cavity', *Toxicol. Appl. Pharmacol.*, vol. 387, p. 114847, Jan. 2020, doi: 10.1016/j.taap.2019.114847.

[196] D. M. Bernstein *et al.*, 'Evaluation of the exposure, dose-response and fate in the lung and pleura of chrysotile-containing brake dust compared to TiO2, chrysotile, crocidolite or amosite asbestos in a 90-day quantitative inhalation toxicology study – Interim results Part 1: Experimental design, aerosol exposure, lung burdens and BAL', *Toxicol. Appl. Pharmacol.*, vol. 387, p. 114856, Jan. 2020, doi: 10.1016/j.taap.2019.114856.

[197] D. M. Bernstein, B. Toth, R. A. Rogers, P. Kunzendorf, J. I. Phillips, and D. Schaudien, 'Final results from a 90-day quantitative inhalation toxicology study evaluating the dose-response and fate in the lung and pleura of chrysotile-containing brake dust compared to TiO2, chrysotile, crocidolite or amosite asbestos: Histopathological examination, confocal microscopy and collagen quantification of the lung and pleural cavity', *Toxicol. Appl. Pharmacol.*, vol. 424, p. 115598, Aug. 2021, doi: 10.1016/j.taap.2021.115598.

[198] D. M. Bernstein *et al.*, 'Evaluation of the dose-response and fate in the lung and pleura of chrysotile-containing brake dust compared to chrysotile or crocidolite asbestos in a 28-day quantitative inhalation toxicology study', *Toxicol. Appl. Pharmacol.*, vol. 351, pp. 74–92, Jul. 2018, doi: 10.1016/j.taap.2018.04.033.

[199] D. M. Bernstein *et al.*, 'Evaluation of the deposition, translocation and pathological response of brake dust with and without added chrysotile in comparison to crocidolite asbestos following short-term inhalation: Interim results', *Toxicol. Appl. Pharmacol.*, vol. 276, no. 1, pp. 28–46, Apr. 2014, doi: 10.1016/j.taap.2014.01.016.

[200] D. M. Bernstein *et al.*, 'Evaluation of the fate and pathological response in the lung and pleura of brake dust alone and in combination with added chrysotile compared to crocidolite asbestos following short-term inhalation exposure', *Toxicol. Appl. Pharmacol.*, vol. 283, no. 1, pp. 20–34, Feb. 2015, doi: 10.1016/j.taap.2014.12.012.

Glossary

Battery Electric Vehicle (BEV)

A vehicle relying for power only on an electric motor and a battery, which can be recharged using an electric socket.

Coarse Particles (PM_{10})

Total mass of particles emitted with a diameter of 2.510 µm.

Economic Commission for Europe

Brake pads certified by regulation ECE R90 for their safety, **pads (ECE pads)** quality and reliability. They are low-metallic pads.

European Institute of Innovation and Technology Urban Mobility (EIT UM)

Initiative of EIT, acting to accelerate positive change on mobility to make urban spaces more liveable

Emission Factor (EF)

Normalized coefficient that correlates the amount of a pollutant to the source that produces it. In the case of road transport, emission factors are usually expressed in mass per kilometre driven by a vehicle (mg/km/veh).

Fine Particles ($PM_{2.5}$)

Total mass of particles emitted with a diameter less than 2.5 µm.

Friction Layer

The part of the brake pad that comes into direct contact with the brake rotor upon a braking event. Usually, a composite material containing a binder, an additive (reinforcement), one or more fillers, and an abrasion component.

Greater London Authority (GLA)

The governing body responsible for overseeing the administration of Greater London, which includes the City of London and its 32 boroughs.

Grey Cast Iron (GCI)

An alloy typically containing about 96 % iron (Fe), 2.5 – 3.8 % carbon (C), 1.1 – 2.85 % silicon (Si), and very small amounts of manganese (Mn), phosphorus (P), and sulphur (S).

Heavy-Duty Vehicle (HDV)

A commercial vehicle heavier than 3.5 tonnes or a passenger vehicle with 8 seats or more.

Heavy-Goods Vehicle (HGV)

A vehicle heavier than 3.5 tonnes specifically designed for transporting goods.

Hybrid Electric Vehicle (HEV)

A vehicle with both an internal combustion engine and an electric motor and battery, operating on both petrol and electric power.

London Atmospheric Emissions

London's database tracking the emissions of air pollutants **Inventory (LAEI)** across the Greater London area.

Light-Duty Vehicle (LDV)

A passenger car or light commercial vehicle no heavier than 3.5 tonnes.

Light Goods Vehicle (LGV)

A vehicle specifically designed for transporting goods no heavier than 3.5 tonnes.

Low-Metallic pads (LM pads)

Brake pads containing relatively low amounts of metallic materials. They can also be found in the literature as low steel or ECE pads.

Microplastics

Microplastics are fragments of any type of plastic less than 5 mm in length, and cause pollution by entering natural ecosystems from a variety of sources, including tyres, cosmetics, clothing, food packaging, and industrial processes.

Non-Asbestos Organic (NAO) pads

Brake pad type, which is a mixture of materials including aramid fiber, copper fiber, glass fiber, rubber, graphite and resin. It is used in vehicles outside Europe.

Non-Exhaust Emissions (NEEs)

Pollutants released into the ambient from sources other than the tailpipes of vehicles. They include brake, tyre and road wear.

Particle Mass (PM)

The total mass (weight) of particles emitted.

Particle Number (PN)

The total number of particles emitted as airborne.

Particle Number 10 (PN_{10})

The total number of particles emitted with a diameter more than 10 nanometres.

Particle Number 23 (PN_{23})

The total number of particles emitted with a diameter more than 23 nanometres.

Particulate Matter (PM)

A complex mixture of very small solid and liquid particles suspended in the air, characterized by various origins, sizes and chemical compositions.

Plug-in Hybrid Electric Vehicle (PHEV)

A vehicle with both an internal combustion engine and an electric motor and a battery that can be recharged using an electric socket.

Receptor modelling

The process of analysing the chemical composition of air in urban areas to identify specific tracer elements, characteristic of each emission source (brake/tyre/road wear).

Regenerative braking

A system in electrified vehicles that recaptures kinetic energy from braking to recharge the battery without using mechanical brakes.

Studded tyres

Winter tyres with metal studs embedded in the tread, offering improved traction on roads with ice or snow.

Transport for London (TfL)

Functional body of the Greater London Authority, responsible for London's transport system. Its primary role is to implement the Mayor of London's Transport Strategy and manage transport services to, from and within London.

Ultrafine Particles (UFPs, $PM_{0.1}$)

Total mass of particles emitted with a diameter less than 0.1 µm.

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